Requirements for shaft seals for HLW repositories in Germany

- Technical Report -
Translated extraction from (Kudla et al, 2013 – chapter 4)

Michael Jobmann
DBE TECHNOLOGY GmbH, Eschenstraße 55, D-31224 Peine, Germany
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Background

The primary objective of repository research is to establish a scientific and technological basis for a safe disposal of high-level radioactive waste. In addition to the technical feasibility, one major goal is the feasibility of suitable safety assessments. In this context, the safety assessments of the multi-barrier system, which consists of the geologic barrier and the necessary geotechnical barriers, e.g., containers and drift or shaft seals, are of major importance. These individual components of the sealing concept, which often are arranged in parallel, are to ensure the safe closure of all underground openings after waste emplacement and thus, together with the geological barrier, to ensure the long-term isolation of the radioactive waste.

As part of the German disposal concept the access shafts to the underground facilities represent the main pathway between the underground repository and the biosphere and therefore play an important role in the safety case. Prior to the development of a closure concept the requirements for the sealing systems are to be defined. This report compiles current requirements for shaft sealing systems in Germany in a systematic way.

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1 Requirements for shaft seals

The following section describes the general and specific requirements that need to be met by shaft sealing constructions in rock salt and argillaceous rock in Germany.

1.1 General safety requirements

The new safety requirements issued by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) set out the safety standards that a repository site for heat-generating radioactive waste in deep geological formations must fulfil (BMU, 2010). They also cover the geotechnical barrier system and, thus, the shaft seal. Pertinent information can be found in chapters 7.2, 7.3, and 8.7 of the safety requirements, excerpts from which are quoted in the following:

Chapter 7.2: Prior to any major decision pursuant to chapter 5.1, a comprehensive, site-specific safety analysis and safety assessment covering a period of one million years must be carried out to provide evidence of long-term safety. This shall comprise all information, analyses and arguments verifying the long-term safety of the final repository, and shall justify the reasons why this assessment is to be trusted. In particular, this assessment and the documentation thereof should include the following points:

…..The quality-assured implementability of requirements pertaining to technical barriers, the identification, characterization and modelling of safety-relevant processes, together with confidence-building in this regard and qualification of the models, the comprehensive identification and analysis of safety-relevant scenarios and their allocation to probability categories pursuant to chapter 6, and the representation and implementation of a systematic strategy for the identification, evaluation and handling of uncertainties.

For the shaft seal, this means that all processes that affect individual components of the shaft sealing system need to be identified and their consequences need to be assessed based on a scenario analysis (in-depth verification).

Moreover, this assessment of long-term safety must be based on the following findings as a minimum requirement:
Long-term statement on the integrity of the isolating rock zone: For probable developments, evidence must be provided on the basis of a long-term geoscientific prognosis verifying that the integrity of the isolating rock zone is guaranteed throughout the reference period of 1 million years. To this end, the applicant should provide a clear spatial and temporal definition of the isolating rock zone and should demonstrate that, with due regard for the emplaced waste and technical barriers\(^1\), the formation of secondary water pathways within the isolating rock zone which could lead to the ingress or escape of potentially contaminated aqueous solutions can be excluded, and that any pore water that may be present in the isolating rock zone does not participate in the hydrogeological cycle outside of the isolating rock zone as defined by water legislation.

Strictly speaking, the latter means that if components of the shaft sealing system are located in the isolating rock zone, the velocities of advective transport processes in these components have to be comparable with those of diffusive transport processes.

In rock salt and argillaceous rock, the integrity of the isolating rock zone should additionally be tested using the following criteria:
The anticipated stresses should not exceed the dilatancy strength of the rock formations in the isolating rock zone outside of the disturbed rock zone. …..

\(^1\) Note: The authors assume that this comprises the technical and geotechnical barriers.
For the components of the shaft seal, e.g. the sealing elements that build up swelling pressure in order to obtain their sealing function, this means that the swelling pressure shall not exceed the rock strength.

Proof of the robustness of the final repository system’s technical components:
The long-term robustness of the technical components of the final repository system must be forecasted and described on the basis of theoretical considerations. If technical barriers perform significant safety functions with regard to long-term safety and are subject to special requirements, and if there are no recognised technical rules available in this regard, as a general rule, their manufacture, construction and function must have been tested. Testing must include quality assurance in accordance with the state of the art. The need for testing may be waived if the robustness of these structures, i.e. their insensitivity to internal and external influences and failures, can be proven by some other means, or if safety reserves exist to an extent that obviates the need for testing.

When providing proof of integrity and containment, allowance must be made for technically unavoidable barrier perforations (such as shafts) and backfilling of the final repository. It is necessary to demonstrate that the integrity required of the geological barrier and its guaranteed containment are preserved even when technical sealing structures and the backfill thereof are taken into account. Inter alia, this should be verified by analysing the stress conditions and properties of the construction materials that are decisive for proper functioning of the technical sealing structures. Adequate load capacity and durability of such construction materials must be proven for the same length of time as that for which proper functioning of the structures must be guaranteed. Where necessary, immediately effective barriers must ensure containment of the waste until such time as barriers with a long-term action have developed their full potential.

The statements quoted above are direct requirements for the components of a shaft seal.

Chapter 7.3: For a numerical analysis of the final repository’s long-term behaviour with respect to … properties of the sealing structures, deterministic calculations should be based on the most realistic modelling possible (e.g. median values as input parameters). The objectives of these calculations are:
- To demonstrate the anticipated system behaviour
- To derive (where necessary) time-dependent requirements applicable to the components of the repository system …

Additionally, uncertainty and sensitivity analyses must be carried out in order to highlight the potential solution space and be able to estimate the influence of uncertainties. Model uncertainties must also be taken into account. Compliance with numerical criteria resulting or derived from these safety analyses must be assured with an adequate degree of reliability, with due regard for the uncertainties. Any numerical violations of these criteria resulting from the analyses should be evaluated for relevance.

These directives refer to the long-term safety case. Requirements on the geotechnical barriers and, thus, on the shaft sealing construction that are derived from the long-term safety analysis are to be identified and taken into account when designing the shaft seal.

Chapter 8.7: The containment capacity of the final repository must be based on a range of different barriers with varying safety functions. With regard to the reliability of containment, the interactions must be optimized between these barriers in terms of redundancy and diversity. Allowance must be made for the hazard potential of the waste and the varying actions of the barriers in the different time zones. The safety of the final repository after decommissioning must therefore be ensured by means of a robust, graduated barrier system that fulfils its functions in a passive, maintenance-free manner and which continues to ensure adequate functionality even if individual barriers fail to develop their full effect.
For the shaft seal, this means that redundancy and diversity need to be taken into account in the shaft design, e.g. by designing several sealing elements made of various materials. But for the repository safety evaluation, this means that the shaft seal needs to be assessed together with the other barriers (e.g. the drift seals). This is especially significant with regard to the period of effectiveness of the shaft sealing construction.

1.2 Requirements pursuant to the safety and verification concepts

Within the scope of the R&D project *ISIBEL* (Krone et al., 2008), (Krone et al., 2010) and later in the “Preliminary Safety assessment of the Gorleben site” (VSG), which was based on *ISIBEL*, a safety assessment and verification concept that takes into account the safety requirements issued by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) was developed for the very first time. This concept further substantiates the safety requirements of BMU.

The safety concept describes the factors and measures needed to achieve and ensure the long-term safety of a repository at a given site. The verification concept identifies the assessments and verifications that need to be carried out in order to demonstrate that the safety requirements are met and especially to demonstrate the safe containment of the radioactive waste in the repository (Mönig et al., 2012).

Within the scope of the R&D project *AnSichT*, an analogue safety and verification concept is currently being developed for generic repository sites in claystone (Jobmann, 2011). From both concepts, specific requirements for shaft sealing constructions and their design can be derived (Fig. 1).

![Fig. 1: Structural connection between safety requirements, safety concepts and concepts for shaft sealing systems](image-url)

Regarding the design of shaft sealing constructions, the safety and verification concept for rock salt for example stipulates:

…..Some of the technical measures are to seal the inevitable penetrations of the geologic barrier quickly and effectively and to thus contribute to restoring its integrity in the long term. They are also to prevent system developments that could lead to an impairment of the integrity of the isolating rock mass. The following activities are to be carried out:
High quality sealing constructions with a specific hydraulic resistance are to be erected in the shafts and in the access drifts between the infrastructure area and the emplacement areas. The sealing constructions have to be sufficiently tight until the hydraulic resistance of the compacting crushed salt backfill is high enough to prevent that brines and solutions reach the waste or to limit their access to the extent that the safety requirements of BMU, especially the safety principles and the requirements on the repository design, are met. Based on these conditions, minimum periods of barrier effectiveness are determined that are at least as long as or longer than the time required for adequate backfill compaction. The design of the sealing constructions is based on load cases that are to cover the range of repository developments that are possible during the barriers' required periods of effectiveness.

Thus, one important requirement for the design of shaft seals in rock salt is that the shaft seal must be sufficiently effective from the beginning until the hydraulic resistance of the compacting crushed salt backfill is high enough. Another requirement is that in the verification process, a site-specific FEP catalogue (FEP = features, events, and processes) be taken into account and that all FEPs be identified that could affect the components of the shaft seal, where a distinction is to be made between probable and less probable processes. Based on these FEPs, scenarios for probable and less probable developments will be identified that will be taken into account in the subsequent verification process. Figure 2 gives an overview of the structural procedure.

![Structural procedure to assess the safety of a repository site in rock salt](image)

The safety and verification concept for a repository site in salt (Mönig et al., 2012) stipulates that the containment capacity of the isolating rock mass is optimum if there is no contact between solutions and waste and if no radionuclides are released via the pathway for gas. According to the safety and verification concept, safe containment is still given even if there is contact between brines and waste but if no radionuclides are released from the isolating rock mass, neither via the pathway for solutions nor via the pathway for gas.
The primary goal of the design of a sealing system in a salt formation is to prevent a continuous solution path between overlying rock and waste in the reference scenario and the related probable repository evolutions. The goal in the design for less likely, alternative scenarios is to prevent the release of dissolved radionuclides and contaminated solutions from the isolating rock mass and to, thus, guarantee safe containments with respect to transport via solutions. If in the course of the assessment, i.e. when analyzing release scenarios, supplementary requirements on the functional elements of the shaft seal are identified, they are to be taken into account in a subsequent, advanced verification process (optimization). This means that requirements on functional elements may have to be optimized in an iterative process and should not be immutable from the outset.

Due to this iterative optimization, it is necessary to prepare a draft or preliminary design of the shaft seal. This draft design will provide a basis regarding the dimensions and properties of the individual functional elements. Furthermore, it will show if the construction is generally feasible. For the shaft seal, a chemical, mechanical, and hydraulic draft design is, thus, to be prepared. The draft design of the sealing system will not take into account the migration path for gas, as the parameters of the latter cannot be determined until an iterative process is carried out that takes into account the results of analyses concerning release scenarios. The migration path for gas will not be considered and appraised until a subsequent advanced verification is carried out. For the pathway for gas, it is important to impede or prevent fluid migration to the waste. This will limit gas formation and thus the transport capacity of the pathway for gas and will also restrict the build-up of high gas pressures significantly. The resulting parameters for the pathway for gas and the corresponding requirements on the sealing system can thus only be taken into account in a site-specific optimization.

The draft design of the shaft seal needs to take into account those FEPs that could lead to an impairment of its effectiveness. The FEPs that may affect the components of a shaft seal in rock salt were identified in (Wolf et al., 2012) and allocated to scenarios in (Beuth et al., 2012). Table 1 lists the likely, primary FEPs that may lead to impairment. The information is based on (Beuth et al., 2012). The less likely FEPs that may lead to impairment are listed in Table 1.

FEP catalogues for generic repository sites in two different claystone formations in Germany are currently being compiled within the scope of the R&D project AnSichT (Jobmann, 2011).

### Table 1: Primary FEPs that may impair the effectiveness of the shaft seal in rock salt

<table>
<thead>
<tr>
<th>FEP No.</th>
<th>FEP Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2.03.01</td>
<td>Earthquake</td>
</tr>
<tr>
<td>1.2.09.01</td>
<td>Diapirism</td>
</tr>
<tr>
<td>1.2.09.02</td>
<td>Subrosion</td>
</tr>
<tr>
<td>1.3.05.03</td>
<td>Formation of glacial channels</td>
</tr>
<tr>
<td>2.1.05.04</td>
<td>Alteration of seals</td>
</tr>
<tr>
<td>2.1.07.01</td>
<td>Convergence</td>
</tr>
<tr>
<td>2.1.07.02</td>
<td>Fluid pressure changes</td>
</tr>
<tr>
<td>2.1.07.04</td>
<td>Volume changes in materials, not temperature induced</td>
</tr>
<tr>
<td>2.1.07.07</td>
<td>Displacement of sealing elements</td>
</tr>
<tr>
<td>2.1.08.08</td>
<td>Swelling of bentonite</td>
</tr>
<tr>
<td>2.1.09.02</td>
<td>Dissolution and precipitation</td>
</tr>
<tr>
<td>2.1.09.06</td>
<td>Corrosion of materials</td>
</tr>
<tr>
<td>2.2.01.01</td>
<td>Excavation damaged zone</td>
</tr>
<tr>
<td>2.2.06.01</td>
<td>Change in stress state and stress redistribution</td>
</tr>
</tbody>
</table>

However, the FEP analysis alone is not sufficient. Only the scenario analysis, which is based on the relevant FEPs, allows drawing conclusions on possible impairments and, thus, on possible changes in the draft design and the dimensions.

### Table 2: Less likely FEPs that may affect the shaft seal in rock salt

<table>
<thead>
<tr>
<th>FEP No.</th>
<th>FEP Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.07.05</td>
<td>Premature failure of a shaft seal</td>
</tr>
<tr>
<td>2.1.08.05</td>
<td>Channel formation in sealing elements</td>
</tr>
</tbody>
</table>
The maximum functional period of the sealing systems in rock salt is hence initially limited by the occurrence of the next glacial period, which – according to geologic long-term forecasts – will occur in approx. 50,000 years (Mrugalla, 2011). As the hydrogeologic conditions in the overburden are of fundamental importance for several parts of the sealing system, especially the shaft seal, but as a forecast of the hydrogeologic conditions during and after the next glacial period is not possible, the functional period of the sealing system is limited to the period until the next glacial period starts. Subsequently, it needs to be assessed, if the crushed salt backfill will in fact attain its sealing function in a period < 50,000 years.

Current forecast calculations within the scope of the VSG show that the crushed salt backfill will attain an adequate degree of compaction after approximately 1,000 years (Czaikowski & Wieczorek, 2012). For the shaft seal, a functional period of 1,000 years would thus be applicable. In this case, the shaft seal alone, i.e. without the support from drift seals, has to be able to prevent the influx of solutions until the crushed salt backfill in the access drifts attains adequate compaction properties. This results in the hydraulic requirement that after the first passage of fluid, the integral flow rate through the entire sealing system has to be so low that the inflowing solution does not reach the crushed salt backfill in the access drifts until after 1,000 years.

This is different for repository sites in claystone formations, as in this case, the repository is not completely dry as is the case in salt, because porewaters are present everywhere from the outset. This means that in claystone formations, the primary function of the shaft seal is not to impede or prevent inflow of solution from the overburden to the waste in order to impede the onset of corrosion. Regarding the design of shaft seals, the first draft of the safety and verification concept for claystone (Jobmann, 2011) states:

…..Safe containment and thus the safety of the repository are characterized by the fact that the radioactive waste mainly remains at the location of emplacement and that – as stipulated in the safety requirements – at the most, only small and defined quantities leave the isolating rock mass. Safe containment is to be ensured by the properties of the claystone in the isolating rock mass in conjunction with the engineered barrier system. Safe containment of the radioactive waste relies on three characteristics that are provided by the host rock, the sealing construction, and the backfill materials during the reference period:
Low permeability: The permeability in the claystones considered is so low that a dispersal of hazardous substances in the isolating rock mass by means of advective transport processes is comparable with a dispersal by means of diffusive transport processes. The low permeabilities of the sealing constructions and the backfill material additionally impede advective flow along the excavated voids. Thus, this is also true for the shaft seal.
Geochemical retention: The geochemical environment in the claystone and in the sealing and backfill materials allows a retention and deferment of the transport of radionuclides, especially of actinides, due to sorption and solubility limits. Both processes limit diffusive transport so that a major part of the radioactivity decays in the isolating rock mass during the reference period. The high buffer capacities of the host rock and of the sealing and backfill materials maintain a stable geochemical environment throughout the reference period. …..

The main requirements for a shaft seal are, thus, prevention of advective fluid flow from the repository or out of the isolating rock mass, maintenance of a stable geochemical environment, and the use of materials with high sorption capacity.

With slight variation, the structural procedure of the safety assessment and of the verification process is similar to that for a repository site in salt (Figure 3).
1.3 Requirements in accordance with the engineering verifications of functionality

The design of the sealing system should be based on the applicable technical standards and regulations (DIN EN 1997-1), (DIN EN 1990), (DGCT 1997), (DAfStb 2004), which aim at verifying the proper reliability level of the (barrier) construction. The methodology is described in a separate report (Herold & Müller-Höppe, 2013). The individual functional components of a shaft seal have to be designed in such a way that their functionality can be verified in accordance with the safety demonstration concept. The following individual verifications have to be carried out:

1. Demonstration of sufficient hydraulic resistance (demonstration of tightness)
2. Demonstration of stability (demonstration of integrity)
3. Demonstration of feasibility

These three verifications are essential for demonstrating the long-term safety of the shaft seal.

The demonstration of sufficient tightness does not cover the sealing elements alone but needs to take into account the contact zones and the excavation damaged zone as well; i.e., sufficient hydraulic tightness is determined across the integral tightness of these three components (Herold & Müller-Höppe, 2013). The hydraulic tightness of the excavation damaged zone can be improved by recutting severely damaged areas close to the side walls. This also complies with the requirements from other guidelines (cf. chapter 1.6). One condition is that the depth of the excavation damaged zone is known. The depth can and should be determined by means of calculations as well as by means of in situ measurements. After the permeable zone of the excavation damaged zone has been trimmed, the sealing elements
should be installed promptly as trimming causes the EDZ to “loosen” again, where the speed of the “loosening” may vary. The converging rock mass on the one side and the counter-pressure of the sealing element on the other side – especially if materials capable of swelling are used – cause the permeability of the damaged zone to decrease over time. This process has the same effect on the contact zone between sealing element and rock mass. If a sealing element needs to be effective immediately, it has to be constructed from material that is capable of swelling or the material has to have other properties allowing it to tightly connect with the rock mass (e.g. bitumen or asphalt) and to maintain this connection even under fluid pressure, thus sealing the contact zone. In addition to this, the “loosened” zone that forms after the EDZ has been trimmed may have to be improved by means of technical injection measures.

The demonstration of integrity (Herold & Müller-Höppe, 2013) consists of the following:

1. Demonstrability of structural stability
2. Demonstrability of crack limitation
3. Demonstrability of deformation limitation
4. Demonstrability of filter stability (erosion, suffosion)
5. Demonstrability of durability/long-term stability

Deformation and crack limitation can be limited by constructing the sealing elements from material that bonds adhesively with the shaft contour. This would lead to limited settlement. A sealing element that bonds adhesively with the shaft contour can also act as an abutment i.e. would have a two-fold function.

If non-cohesive, non-self-supporting sealing material like bentonite is used, a further possibility to limit deformation is to install the sealing element on top of a support column with limited settlement capacity. This requires that the material and the design of the support column are resistant to deformation. According to (Wagner, 2005), the settlement is not to exceed 3 % of the seal's length. This settlement value is derived from the permissible degree of loosening in the sealing element at which the swelling pressure is just about sufficient. An alternative to granular material with low settlement properties is the use of a cohesive support column that has similar support properties.

Filter stability can be achieved by avoiding erosion and suffosion processes in the sealing element. As the gravitational force and the fluid inflow from aquifers in the overburden act in the same direction, there may be an increased risk for erosion and suffosion, especially in the saturation phase and if the sealing element is made of fine-grained aggregate (e.g. bentonite). This has to be mitigated or prevented by design measures; i.e., in order to avoid erosion and suffusion, it is imperative to use filter layers in the sealing element.

In any case the dimensioning of the functional elements, their location in the system as a whole, and the materials are to be selected in such a way that the individual verifications mentioned above can be carried out. For the materials to be used this means in particular that for each material, a complete and consistent data set needs to be available that characterizes the material behaviour and its properties. Thus, before a material is proposed for a functional element, it has to be characterized in the appropriate way.

1.4 Requirements derived from site-specific boundary conditions

1.4.1 Geologic boundary conditions

Choice of material for and location in depth of individual functional elements depend on the conditions specific to the respective site. If the shaft that is to be sealed penetrates fault
zones or zones that may bear fluids, the fluid-bearing zones need to be sealed by means of sealing elements that have sufficient overlap below and above the fault zone.

In shaft Gorleben, for example, the stratigraphic units are folded several times. Especially the so-called *Gorleben-Bank*, a tightly bedded anhydrite bank, is penetrated three times. As the material properties of anhydrite are significantly different from those of the surrounding rock salt, it cannot be excluded that it may bear fluids at a later date. The shaft sealing concept that was developed within the scope of the preliminary safety analysis Gorleben takes this circumstance into account by stipulating that sealing elements with corresponding overlap be installed at the Gorleben Bank.

If – depending on the location or the depth – different saline solutions, like NaCl- or MgCl-solutions, are present or may be formed, the materials for the sealing elements are to be selected such that no significant corrosion occurs if such solutions appear.

Sealing elements made of material that is not capable of swelling (e.g. salt concrete) are to be located at the lowest possible point in the shaft. As the stress deviator increases with increasing depth, a placement of the element as deep as possible is advantageous for accelerating the convergence of the surrounding rock salt. The stress deviator determines the initial speed with which the salt converges onto the sealing element and, thus, the duration and magnitude of the load on the sealing element. The deeper it is placed, the faster and higher the load.

According to current concepts, a potential site is first investigated at an exploration level. Waste containers are to be emplaced on an emplacement level that is to be located below the exploration level. A shaft sealing concept is to take into account that the emplacement level is to be separated from other levels by a sealing element.

Shaft sealing concepts for potentially suitable repository sites in claystone particularly need to take into account that, where clayey and sandy facies alternate, sealing elements are to be located in the clayey facies to prevent fluid migration through the sandy facies passing the sealing elements. These alternating strata are for example present in the clays of the Lower Cretaceous of the Niedersächsisches Becken (lower-saxony basin), which – according to studies carried out so far – seem to be potentially suitable (Jobmann, 2011), (Hoth et al., 2007), (Jobmann et al., 2007).

Within the scope of the R&D project *AnSichT* (Jobmann, 2011) generic models for repository sites in two different claystone formations are currently being developed. Detailed statements on the site-specific boundary conditions for shaft seals in Germany are not possible before the generic models have been completed.

1.4.2 Hydrogeologic boundary conditions

For the design of a sealing system in rock salt, the hydrogeologic boundary conditions in the vicinity of the shafts are of fundamental importance with regard to the goal to prevent inflow of saline solutions via the shafts to the emplaced waste. In the vicinity of the shafts Gorleben 1 and Gorleben 2, for example, several groundwater levels are present that separate aquifers with high capacities from aquitards. Functional elements in this section of the shaft may not have the function to seal the repository, but the separation of the groundwater levels is to be maintained as far as possible. This is to be taken into account in the design. Concerning the primary goal to prevent a continuous migration path to the radioactive waste in the rock salt, the relevant impacts on the sealing system that need to be controlled are the practically unlimited water amounts from the overburden which may be present up to the surface if the pressure build-up rates are high. Limited brine volumes, which are present in the
salt dome, can however be neglected in the first approach. Thus, the shaft seal is the primary seal while drift and borehole seals are secondary, redundant seals.

The components of the shaft seal are to be designed to withstand the maximum possible fluid pressure at the site plus an additional 50 m (fixed) due to climate-induced sea-level changes.

1.5 Requirements derived from other specifications

The following specifications (OCZ, 1996), (Schmidt et al., 1995), (Kappei & Eikmeier, 2006) are based on the experience gained in the decommissioning and securing of shafts in German salt mines in the past 80 years:

- Shafts in rock salt are to be completely backfilled after decommissioning.
- Shaft furnitures should be completely removed prior to backfilling if this does not pose any occupational safety risks.
- Existing water-tight linings should not be removed.
- Liners in horizons where seals are to be placed shall be removed to avoid leakages and infiltrations.
- In horizons where seals are to be placed, the excavation damaged zone in the shaft wall shall be removed as far as possible.
- The entrances to the drifts are to be secured against movements of the filling column.
- For sealing elements in the shaft made of materials that are not capable of swelling it needs to be assured that they are build in direct contact with the rock mass allowing the rock convergence to tighten the contact zone as fast as possible.
- The backfill columns are to be installed in a dry environment.

2 Compilation of requirements

The following table gives a structural compilation of the requirements mentioned in the previous sections.

Table 3: Overview of requirements for shaft seals

<table>
<thead>
<tr>
<th>Source</th>
<th>Requirement</th>
<th>Rock salt</th>
<th>Claystone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety requirements of BMU</td>
<td>Process analysis of impacts on shaft seal</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>If components of the shaft seal are located in the isolating rock mass, the velocities of the transport processes in the components have to be comparable with those of diffusive transport processes (sufficiently low permeability)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Swelling pressures in the sealing elements are not to exceed the rock strength</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>If there are no technical regulations for geotechnical barriers, their construction, erection and function generally have to be verified through practical tests. (May not be necessary, if robustness can be verified by other means or if sufficient safety margins exist.)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>To verify the integrity of the structure, the relevant load cases and construction material properties are to be analyzed. Sufficient load bearing capacity and resistance to ageing of the construction material is to be verified for the same period that the structures need to be fully functional.</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>As far as necessary, immediately effective barriers have to isolate the waste for the period where barriers that are effective in the long term have not yet become completely effective.</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Source | Requirement | Rock salt | Claystone
--- | --- | --- | ---
<p>| • Possible requirements resulting from an analysis of release scenarios have to be identified and taken into account. | X | X |
| • If possible, redundancy and diversity are to be integrated in the shaft seal, e.g. by using several sealing elements made of different materials. | X | X |
| • The shaft seal in combination with the other barriers (e.g. drift seals) is to be assessed with regard to its importance for the safety of the repository e.g. to determine the required period of effectiveness. | X | X |
| Safety and verification concepts | • Maximum period of effectiveness: 50,000 years (next glacial period). Limitations regarding sealing concept (rock salt): The shaft seal has to be sufficiently tight until the hydraulic resistance of the compacting crushed salt backfill is sufficiently high. (according to current estimates, approx. 1,000 years) Consequently, the volumetric flow has to be so low that inflowing brines do not reach the crushed salt backfill in the access drifts until after 1000 years (hydraulic requirement). | X | - |
| | • Maximum period of effectiveness: 50,000 years (next glacial period). Limitations regarding sealing concept (claystone): still pending | - | X |
| | • Draft design of the shaft seal (dimensioning, - properties and demonstration of generell feasibility) | X | X |
| | • Consequence analysis taking into account a FEP list with probable and less probable processes. Resulting requirements on functional elements are to be taken into account (if necessary, iterative optimization). | X | X |
| | • Prevention of advective fluid flow out of the repository and out of the isolating rock mass. | - | X |
| | • Maintaining a stable geochemical environment | - | X |
| | • Use of material with high sorption capacity | - | X |
| Technical functional verification | • The design of the sealing system should be based on the technical standards and regulations DIN EN 1997-1 Eurocode 7, DIN EN 1990 Eurocode, DGGT-GDA recommendations and DAFStb guideline 2004. | X | X |
| | • The individual functional elements of a shaft seal are to be designed in such a way that a functional verification pursuant to the demonstration concept can be carried out. | X | X |
| | • To demonstrate sufficient hydraulic tightness, the individual elements on their own and in combination with the contact zone and the excavation damaged zone are to be considered (integral tightness). | X | X |
| | • In sections where sealing elements are to be located, the excavation damaged zone is to be removed to an appropriate depth. | X | X |
| | • If the sealing concept stipulates that a sealing element is to be effective immediately, the sealing element has to be either constructed of material capable of swelling or a material has to be used that - due to other properties - is in direct contact with the rock and is able to maintain this contact even under fluid pressure (e.g. bitumen or asphalt) so that the contact zone is sealed. In addition to this, the &quot;loosened&quot; zone that forms after the EDZ has been trimmed may have to be improved by means of technical injection measures. | X | X |
| | • If non-cohesive, non-self-supporting sealing material is used, a supporting column with limited settlement capacity (settlement max. 3 % of the seal’s length) is to be installed. | X | X |</p>
<table>
<thead>
<tr>
<th>Source</th>
<th>Requirement</th>
<th>Rock salt</th>
<th>Claystone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Site-specific boundary conditions</strong></td>
<td>• If the shaft to be sealed penetrates fault zones or zones that may bear fluids, the fluid-bearing zones need to be sealed by means of sealing elements that have sufficient overlap.</td>
<td>X</td>
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<td>• Depending on the pore solutions, the materials for the sealing elements are to be selected such that no significant corrosion occurs if such solutions appear.</td>
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<td>• Sealing elements that are not capable of swelling are to be positioned at the lowest possible point in the shaft.</td>
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<td></td>
<td>• The emplacement level is to be isolated from other levels (e.g. exploration level) by means of a sealing element.</td>
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<td></td>
<td>• Where clayey and sandy facies alternate, sealing elements are to be located in the clayey facies to prevent fluid migration through the sandy facies around the barrier.</td>
<td>X</td>
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<td>• If several aquifers are present, an interconnection is to be prevented by means of sealing.</td>
<td>–</td>
<td>X</td>
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<td></td>
<td>• The components of the shaft seal are to be designed to withstand the maximum possible vertical fluid pressure at the site plus an additional 50 m (fixed) due to climate-induced sea-level changes.</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>Other requirements</strong></td>
<td>• After decommissioning, shafts are to be completely backfilled.</td>
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<tr>
<td></td>
<td>• Prior to backfilling, shaft furnitures should be completely removed if this does not pose any occupational safety risk.</td>
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<tr>
<td></td>
<td>• Existing water-tight linings in areas where aquifers are present shall not be removed.</td>
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<td></td>
<td>• Liners in horizons where seals are to be placed are removed to avoid leakages and infiltrations.</td>
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<td>X</td>
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<tr>
<td></td>
<td>• In horizons where seals are to be placed, the excavation damaged zone in the shaft wall shall be removed to an appropriate depth.</td>
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<td></td>
<td>• The entrances to the drifts are secured against movement of the filling column.</td>
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<tr>
<td></td>
<td>• Sealing elements in the shaft made of materials that are not capable of swelling (e.g. salt or sorel concrete), need to be in direct and firm contact with the rock mass.</td>
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<tr>
<td></td>
<td>• The backfill columns are installed in a dry environment.</td>
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</tr>
</tbody>
</table>
3 Summary
The general and specific requirements pertaining to the design of shaft sealing constructions, especially in salt and clay formations in Germany, are described. The requirements are derived from the safety requirements released by the Federal Ministry of Nature Conservation (BMU) in 2010, the requirements resulting from existing safety assessment concepts developed in the R&D projects ISIBEL, VSG (salt), and AnSichT (claystone), from functional demonstrations, from site-specific boundary conditions, and from requirements stipulated in other specifications.

In claystone, the following additional requirements need to be taken into account: Prevention of advective fluid flow from the repository or from the isolating rock mass, stable geochemical environment, adjustment to the variability in facies, material and technological requirements for the shaft liners, use of materials with a high sorption capacity. All requirements are summarized.

4 References


Wagner, K: Beitrag zur Bewertung der Sicherheit untertägiger Verschlussbauwerke im Salinargebirge, Dissertation an der TU Bergakademie Freiberg, Freiberg, Institut für Bergbau und Spezialtiefbau. 2005