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RANGERS

Methodology Report on Design and Performance Assessment of Engineered Barrier Systems in a Salt Repository for HLW/SNF

BGE TEC 2024-06

Technical Report

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Contents

List of Figures

List of Tables

1 Introduction

Salt formations are one of the potential host rocks for the final disposal of high-level radioactive waste (HLW) in deep geological repositories, both in Germany and the United States. The safe isolation of radioactive waste in these repositories relies on a multi-barrier system, combining engineered and natural barriers. The natural barrier is provided by the salt rock itself, known for its self-sealing properties and long-term stability. The engineered barrier, on the other hand, comprises sealing components strategically placed within the repository to enhance its containment capabilities. In both Germany and the United States, long-term safety assessments require demonstrating the integrity of the natural barrier for a period of up to 1 million years. Concurrently, the engineered barrier system (EBS) must maintain its structural and functional integrity until the long-term sealing, such as the granular salt backfill material, has re-consolidated to its final low porosity and permeability.

Based on extensive expertise and experience with engineered barriers in salt formations, BGE TECHNOLOGY GmbH and Sandia National Laboratories have partnered to develop a robust methodology for the integrity and performance assessment of EBS in HLW repositories through the RANGERS project. This collaborative effort aims to establish a unified approach to geotechnical engineering, repository design, integrity and performance evaluation of EBS in salt repositories.

This report presents a comprehensive framework for the design and evaluation of EBS in salt-based repositories, offering detailed guidance on regulatory compliance, safety concepts, design and long-term performance. The developed methodology provides a structured pathway for designing and assessing the EBS's performance, aligned with the specific geological site and repository concept. From the selected geological site and repository design, a tailored sealing concept is defined, which forms the basis of the EBS. The overall repository system, comprising the geological site, repository infrastructure, and EBS, is then subjected to a rigorous analysis of Features, Events, and Processes (FEPs). Only FEPs relevant to the EBS are considered, from which the loads and stresses acting on the system are derived. These loads form the foundation for the integrity assessment. The FEPs are also used to evaluate the evolution of the EBS over the reference period in the scope of performance assessment.

By focusing on the long-term structural integrity and containment effectiveness of the EBS, the RANGERS project sets a new standard for the future of safe radioactive waste disposal in salt formations. Through comprehensive performance assessment simulations, this project ensures that the EBS will meet the stringent safety requirements necessary to demonstrate the safety proof of HLW repositories in salt.

2 General Context

Rock salt formations are considered in Germany and in the United State as suitable host rock for the final disposal of radioactive waste. A radioactive waste repository in salt can take advantage of the extremely low connected porosity and practical impermeability of natural rock salt formations to solutions on one hand, and their self-healing ability on the other hand, to achieve long-term secure containment of the disposed waste and its isolation from the biosphere (Kreienmeyer et al., 2008, p. 8). In a repository in rock salt, it is generally assumed that there are no pathways in the host rock that allow the inflow of solutions from the overburden into the disposal areas. Through appropriate exploration, it is ensured that no solution inclusions are encountered in the host rock or that they are emptied during the excavation of the mining structures (Kindlein et al., 2018). This makes rock salt a safe medium for radioactive waste disposal in deep geological formations.

The safety of a repository in a salt formation is based on a multi-barrier concept. The multiple barriers in salt repositories consist of a technical barrier, a geological barrier, the crushed salt backfill serving as long term barrier, and the geotechnical barriers. The technical barrier is provided by the disposal casks. The safety function of the casks is to ensure the safe transport and handling during the operational phase and to ensure the requirements for retrievability and recoverability up to 500 years in Germany (StandAG, 2023). The geological barrier is provided by the salt host rock. The geological barrier aims to ensure the long-term and secure containment of radioactive waste. The effectiveness of a repository in rock salt is highly dependent on the integrity of the geological barrier in the rock formation (Mönig et al., 2012).

Another important barrier for a salt repository is the backfill material, crushed salt. Due to its self-healing properties, this barrier ensures the safe containment of radioactive waste for long periods of time, even beyond the time frame required for quantitative verification (Müller-Hoeppe and Krone, 1999). During the excavation of the mine, the geological barrier is breached, temporarily creating direct pathways from the waste to the biosphere. In addition, in areas close to the excavations, the geologic barrier is damaged and locally weakened. To ensure long-term stability and permanent filling of the cavities, the mined salt rock generated during excavation will be used as backfill material, filling excavations with essentially the same material as the surrounding geological barrier. Over time, the compaction of the backfill material develops a sealing effect comparable to that of the undisturbed geological barrier. The time required to reach the final states can vary from tens to thousands of years. It depends on the convergence rate, moisture content, and ambient temperature. Therefore, additional geotechnical sealing structures such as shaft seals and drift seals are planned, which will provide a specified sealing ability directly at the closure of the repository (Mönig et al., 2012).

According to AkEnd (2002), the closure of shafts holds a similar significance in terms of long-term safety as the function of the geological barrier. In AkEnd (2002), it is recommended: “A repository mine, whose safety case is primarily based on geological barriers, must be sealed with a geotechnical barrier, the shaft seal, in any case.” The shaft seal is the most crucial safety component as it restores the integrity of the containment area (Müller-Hoeppe and Krone, 1999). Its main function is to prevent water or solution ingress from the overlying rock into the repository after its closure. In the event that radionuclides are mobilized during the post-closure phase, the shaft seal ensures their retention within the repository through appropriate sealing measures. The concept of a shaft seal includes sealing components, similar to those of a drift seal, as well as supporting and load-bearing elements Kreienmeyer et al. (2008).

In a repository for radioactive waste, drift seals are of significant importance as a safety element at the edge of the enclosing rock area. The drift seal must seal off the anthropogenic pathways for solution ingress into the repository, thereby compensating for the temporary loss of safety caused by the construction of the repository Orzechowski (2018).

During the post-closure phase, these sealing structures are subject to external influences and alteration processes (e.g., thermal, mechanical, hydrological, and chemical), which may affect their effectiveness throughout the entire assessment period and cannot be definitively proven. Thus, the shaft seals and drift seals must remain sufficiently tight until the hydraulic resistance of the backfill material is high enough to prevent or limit the ingress of solutions to the waste, achieving the protection level specified in the safety requirements (Mönig et al., 2012).

The design of the geotechnical barriers is a challenging task. These structures require a reliable and well-documented verification that extends their safety assessment well into the post-operational phase and includes critical situations, such as the ingress of solutions. The verification procedures from current engineering recommendations and guidelines only address above-ground structures with a lifespan of approximately 100 years and the possibility of maintenance and repair, but not to underground structures that require a post-operational lifespan of several thousand years without active intervention (Orzechowski, 2018). The shaft seal for instance in a salt repository is designed to remain functional until the occurrence of the next ice age, which is estimated to occur in 50,000 years. However, after the ice age, changes in hydrogeological and topographic conditions caused by glaciation introduce significant uncertainty in predicting the chemical composition of infiltrating waters. Consequently, designing robust seals capable of withstanding these uncertain chemical conditions becomes impossible. In later periods, after the ice age, the primary sealing function is achieved by the host rock and the compacted backfill (Rübel et al., 2016). For the drift seals, a similar or longer functional life time can be expected. The shaft seal would be expected to lose its function first, being the first geotechnical structure in contact with corrosive water. After the failure of the shaft, the drift seals would also provide resistance to flow, keeping brine away from the waste. Therefore, a methodological approach to the design of the engineered barrier system over such a long period of time is critical to the overall safety of a repository in salt.

In Germany, significant efforts have been made to design and assess the safety of engineered barrier systems for repositories in salt formations. These efforts are aimed at ensuring the long-term isolation and containment of radioactive waste. Several noteworthy projects exemplify these efforts and are outlined below.

A new approach to evaluating the effectiveness of barriers in a repository system, as proposed by Müller-Hoeppe and Krone (1999), presents a methodology for evaluation the effectiveness of an underground repository system and its geotechnical barriers in a salt host rock. The key aspect is the introduction of a method for estimating the risk posed by a repository. The fundamental assumption is that a mine specifically designed for disposal purposes is excavated in an undisturbed salt formation. After disposal, the mine is sealed using a multi-barrier system, which requires comprehensive evidence for the entire system as well as individual components. No institutional control is planned following the closure of the repository. Referring to past experiences with flooded salt mines, it is noted that while salt itself is impermeable, there is a distinction between the pure material (halite) and the salt rock formation, which is characterized by layering and geometric features. The authors proposes the following definition of tightness as a central argument to assess the safety of the disposal in salt Sanders (2020): *A barrier is considered tight if the penetration front of the contaminated fluids does not reach the opposite end of the barrier within the designated period of exposure.*.

According to Müller-Hoeppe and Krone (1999), previous considerations assumed the premature failure of barriers as a regular load case, and then considered them as flow barriers in the verification process, assuming gradual release of contaminants. However, if barrier failure is assumed as a normal load case, it eliminates the significant advantage of the salt host rock, as the compaction of the backfill is disrupted and it does not become hydraulically resistive. This assumes the occurrence of an event that only happens in exceptional cases. Such an approach is not provided in engineering and buildings standard such as the Eurocode (DIN EN 1990, 2010) or in the regulations for the design of nuclear facilities by the Nuclear Technology Committee (Kerntechnische Ausschuss (KTA), 1988). These standards initially assume the expected behavior of the system during the design process (Müller-Hoeppe and Krone, 1999).

In this context, Müller-Hoeppe and Krone (1999) proposes a verification method using the limit state design concept with partial safety factors for model and material uncertainties, similar to the Eurocode methodology. However, this method focuses on tightness rather than structural stability. The essential steps are as follows: 1. Description of the limit state for which the actions and resistances are determined. 2. Development of models for actions, material properties, and geometric values. The aim is to demonstrate that the limit states are not exceeded using the determined design values and selected models.

The authors also raise concerns about the feasibility of applying verification concepts to probabilistic approaches. Probabilistic verification with a specified confidence level requires a sample size proportional to the reciprocal of the confidence level, which significantly increases computational demands. Given the complexity of the system, this approach appears impractical due to the substantial computational resources required. Only for very improbable scenarios where a low confidence level on the order of 10^{-2} is sufficient, is this fully probabilistic method considered applicable (Müller-Hoeppe and Krone, 1999). However, it is important to note that this statement should be reconsidered in light of the advancements in computational capacities in recent years (Sanders, 2020; Kuhlman et al., 2024).

The approach put forward by Müller-Hoeppe and Krone (1999) has been further developed in the project ISIBEL. The project ISIBEL (Verification and Evaluation of the Instrumentation for the Safety Assessment of High-Level Radioactive Waste Repositories – Buhmann et al. (2008)) provides a systematic inventory of the state of research and development in the disposal of heat-generating radioactive waste. Work package 5 of this project focuses on the status of design and planning of geotechnical barriers. The follow-up project ISIBEL II, called KOMTESSA, incorporated findings from the previous project and mentioned these results in a chapter on geotechnical barriers.

In the ISIBEL project, the effects and resistances are derived from a collection of features, events, and processes (FEP) that are generic to salt repositories and need to be specified for a specific site. The goal of this project is not to provide specific evidence but rather to demonstrate how such evidence can be obtained and that it is theoretically feasible. As described in Müller-Hoeppe and Krone (1999), the aim is to show how the safe containment can be demonstrated through a combination of geological and geotechnical barriers, and how the maximum individual dose or maximum risk can be determined using release scenarios. The regular demonstration in this project does not involve conservative release scenarios but focuses on the safe containment of the waste. Possible developments and their probabilities are derived from a combination of scenario analysis (Buhmann et al., 2008).

The ISIBEL project considered release scenarios but did not perform a detailed analysis of their likelihood of occurrence. In the safety concept, developments outside the probable range of the repository are differentiated from less likely and unlikely developments. Release scenarios (design-based events) are considered for the less likely developments, while the unlikely developments serve to assess their impact and enhance the understanding of the system (Buhmann et al., 2008, 16ff).

Following the proposed approach in Müller-Hoeppe and Krone (1999), the integrity assessment consists of two components. The requirements for hydraulic properties are derived from the long-term safety analysis (LZSA) and need to be demonstrated for geotechnical barriers. Together with the structural integrity evidence, they constitute the functional demonstration for the safety of geotechnical barriers (Buhmann et al., 2008).

The VSG Project (Preliminary Safety Analysis of the Gorleben Site) was a major scientific study undertaken to evaluate the long-term safety and feasibility of using the Gorleben salt dome as a repository for high-level radioactive waste in Germany. VSG integrated previous developments and research efforts, and provided a comprehensive overview. The methods developed in ISIBEL have been refined. Unlike the ISIBEL project, the updated safety requirements of the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU) from 2010 are available in the VSG and can be incorporated (BMU, 2010). This means that the theoretical considerations from previous projects have been transformed into directives by the responsible institution, and policy decisions have been made regarding open questions such as monitoring and the possibility of retrieval.

The VSG safety concept is based on the fundamental safety requirements:

- Integrity concept (continuity and barrier function of the engineered barrier system remain intact),
- Containment concept (rapid and tight containment of waste through salt rock and barriers), and
- Criticality exclusion.

Fourteen objectives and 17 measures are derived to concretize these requirements. Some of them are directly linked to the EBS. From the safety concept, a verification concept is derived. The VSG verification concept demonstrates how compliance with limits and requirements can be quantitatively demonstrated under the measures mentioned in safety concept. It serves as the basis for all work within the system analysis in the project. The verification includes the following aspects:

1. Procedure for delineating the engineered barrier system.

2. Preservation of the engineered barrier system and its components during the verification period.

3. Criticality exclusion.

4. Containment of radioactive waste within the engineered barrier system.

5. Radiological consequences/release scenarios.

The second point specifically addresses the verification of the engineered barrier system. The verification period continues until another barrier can demonstrably fulfill the safety function. During this period, the hydraulic resistance and structural integrity of the EBS must be maintained (Mönig et al., 2012). In this purpose, coupled analyses consider thermal, hydrological, mechanical, and chemical (THMC) processes and examine aspects such as crack limitation, stability, durability, integral permeability, and failure probability that was introduced as verification criteria in the project ISIBEL. Similar to the ISIBEL project, feasibility and robustness must be demonstrated (Mönig et al., 2012).

In the context of the VSG project, Müller-Hoeppe et al. (2012b) proposed a comprehensive design for the engineered barrier system (EBS) specifically tailored to the Gorleben site, which has been extensively studied. This design represents the first of its kind for a high-level radioactive waste repository in Germany. It has since served as a foundation for subsequent research and development, as well as a source of inspiration for EBS designs in other host rock formations. In a subsequent analysis by Müller-Hoeppe et al. (2012a), the proposed design was evaluated to ensure compliance with the safety and verification concept discussed earlier.

To achieve this, geochemical process modeling was employed to simulate dissolution and precipitation processes within the shaft sealing elements. This modeling considered the inflow of brine from the overburden and the resulting changes in solution composition throughout the entire sealing system. Geomechanical process modeling was also conducted to assess the mechanical loads on the sealing elements, including rock pressure and hydraulic pressure, to verify no fracturing would occur. Furthermore, hydraulic assessments were performed to determine the water flow through the sealing system and assess whether the permeability of the system met the required safety function of preventing contact between the waste and external water sources. Based on the results of the performance assessments, design modifications were implemented to finalize the layout of the sealing system.

Building on the pioneering work of Müller-Hoeppe et al. (2012b), the practical design of shaft seals was a focal point of the ELSA project. This project seeks to further advance the knowledge and implementation of shaft seals for repositories of high-level radioactive waste. The insights and findings from Müller-Hoeppe et al. (2012b) have provided valuable inspiration and guidance for the design considerations in the ELSA project. By incorporating the site-specific characteristics of different host rock formations, the project aimed to develop practical and effective designs for shaft seals that ensure the long-term safety and containment of radioactive waste. The focus was on existing and planned shaft seals in repositories located in clay and salt formations. Insights into the use of materials in geotechnical barriers were discussed, which can be applied to the shaft seals examined in this report and incorporated into recommendations. Due to the requirements for sealing former mining shafts outlined in relevant standards, there is a greater wealth of experience in sealing shafts compared to drift seals (Kudla and al., 2020).

Within the ELSA project, a comprehensive analysis was conducted, providing a detailed description of shaft seal systems in various rock formations. This analysis encompassed an in-depth examination of rock mechanics properties, flow and transport processes, and the specific conditions present at each sealing location. It is crucial to consider that shaft seals serve as the primary geotechnical barriers, being the first point of contact for infiltrating solutions from the overlying strata or the shaft itself. As a result, the range of infiltrating solutions for which shaft seals need to be designed is relatively large compared to those encountered at drift seals. This distinction is significant as it directly influences the chemical environment experienced by the drift seals located within the repository, situated behind the shaft seal. Furthermore, it is noteworthy that the presence of geochemically unsaturated brine solutions at the barrier represents a key differentiation from the drift seals within the repository.

During the second phase of the ELSA project (ELSA II), significant advancements were made in the development and testing of functional elements for shaft seals. Extensive laboratory programs have been conducted to refine and evaluate the materials used in shaft seals. Field experiments have been carried out to assess the constructibility of shaft seals, including the backfilling of a mock-up shaft. Additionally, simulations have been performed to analyze the settlement stability of the gravel column in the shaft during seismic events. The results demonstrate that the expected settlement after a seismic event will be within the range of centimeters, indicating the effectiveness of the design in maintaining stability. These findings contribute to the overall improvement and reliability of shaft seals for repositories of high-level radioactive waste (Kudla and al., 2020).

The assessment of safety for underground closure structures in salt rock formations is an important part of the overall process (Wagner, 2005). Given the lack of practical experience in constructing long-term secure underground closure structures, this dissertation presents a semi-probabilistic approach to safety assessment.

For this purpose, distribution functions (deterministic value, normal or log-normal distribution) are defined for the influencing factors of different closure elements, and failure probabilities for individual elements (i.e., bentonite sealing elements, gravel columns) are calculated using these distributions. A deterministic model is established to represent the failure mechanism. Subsequently, input parameters for this model are linked to the stochastic models, and failure probabilities are calculated using the Monte Carlo method (Wagner, 2005, p. 104).

Wagner also acknowledges the need for large sample sizes to determine small failure probabilities as a significant weakness of this method. However, considering the considerably improved computational power today, this statement needs to be reassessed. A maximum volume flow of $Q = 10\ m^3$/year (Wagner, 2005, p. 48) within a demonstration period of one million years is assumed as the limit state for the design. It is emphasized that the imprecise data basis and the difficulty of determining material properties for such long periods make it critical to evaluate the derived nominal values of failure probabilities (Wagner, 2005, p. 38).

Wagner (2005) determines failure probabilities related to the service life for tunnel closure structures ranging from 10^{-4} and $6 \cdot 10^{-3}$. The failure probability can be interpreted as a monotonically increasing function of time during the demonstration period, with failure occurring at a random point in time. Improving the results can be achieved through investigations of input parameters, their probabilities, and the arrangement of redundant elements. The calculated failure probabilities in the study can only describe the considered limit states, making the determination of these limit states a crucial task in the design process (Wagner, 2005, p. 131).

Furthermore, Wagner (2005) notes that a rational determination of the limit value for failure probability is not straightforward. As demonstrated in the past, it is a politically made decision indirectly reflected in the safety requirements of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) through the establishment of limit values. However, the linkage between failure probabilities and compliance with these limits or a limit risk remains the task of the safety case (Wagner, 2005, p. 131).

Orzechowski (2018) presents an approach to reconcile requirements from existing standards with those related to long-term safety for a repository. The relevant standards are based on past experiences and consolidate established knowledge in a methodical and structured manner for practical application. However, the fundamentals for designing repositories significantly deviate from those of existing standards, making their direct transferability uncertain. Two crucial aspects are the extended demonstration period in a repository and the requirement for maintenance-free operation.

In the relevant standards, the demonstration period for typical structures is on the order of 100 years, during which failure can be reasonably excluded. When this period is extended without appropriately considering safety measures, the failure probability for structures increases to an unacceptable level Orzechowski (2018)[pp. 128, 131]. According to Orzechowski (2018), simply increasing the resistance values does not address this issue since it would exceed the magnitude of typical material properties. Furthermore, the problem is exacerbated by the impracticality of maintenance for the closures in the intended system, which rules out later inspections and repairs. Orzechowski (2018) concludes that the validity of the design with the principle of partial safety factors is questionable.

In (Müller-Hoeppe et al., 2017), the assertion by Orzechowski (2018) is reassessed. Müller-Hoeppe et al. argue that if the potential values for the characteristics during the demonstration period are known, there is no basis for simply extrapolating the failure probability from the standards. Such extrapolation relies on a statistical distribution of values that cannot become arbitrarily large while the applicable laws of nature remain valid. This representation may be appropriate for continuous processes (e.g., corrosion) due to the varying deterministic components. However, this statement should be qualified when considering infrequent events (e.g., earthquakes) (Müller-Hoeppe et al., 2017).

Considering the findings in (Keller et al., 2010, pp. 41f), it can be concluded that nominal values for partial safety factors must be determined considering the conditions over the respective functional lifespan of the system. Nonetheless, the fundamental applicability of the method is at least present in some applications.

Orzechowski (2018) also introduces a five-step methodology aimed at combining approaches from standards and long-term safety. In the first step, requirements from both schemes are initially considered separately. Then, conditions and specifications are derived from the FEPs relevant for the design in the chosen scenarios. In the second step, these conditions are compared and supplemented with the requirements from the standards. Subsequently, in step three, the actual planning process for the barrier is carried out. Step four involves comparing the properties with the requirements, leading to either confirmation of the construction or, through iteration, revising the structure or adjusting the basis for the requirements. The fifth step entails documenting the process.

In summary, the design of engineered barrier systems in salt geotechnical barriers has reached a mature state of development. However, designing geotechnical barriers for repositories in salt formations over a long period of time presents significant challenges and requires a reliable and well-documented demonstration of their safety.

Different approaches have been proposed to address these challenges. One approach, as suggested by Müller-Hoeppe and Krone (1999), is based on a semi-probabilistic philosophy that incorporates safety factors to account for the spatial and temporal variability of the materials used in the system.

Another approach, advocated by (Wagner, 2005), is a fully probabilistic method. While this approach provides a more comprehensive assessment of the failure probability and resilience level of the engineered barrier system, it requires a significant amount of computational effort.

The criticism raised by (Orzechowski, 2018) regarding the use of safety factors can be disregarded by carefully considering the underlying physical and chemical processes governing the degradation of the building materials. This consideration helps to better determine the necessary safety factors. Additionally, (Orzechowski, 2018) acknowledges the verification criteria proposed by Müller-Höppe in the ISIBEL project (Buhmann et al., 2008).

Overall, these different approaches and considerations contribute to the ongoing development and improvement of engineered barrier systems for repositories in salt formations. They will be further developed in the present report in a broader context of an engineered barrier system (EBS) centric view of the safety assessment of repositories in salt.

3 Overview of the methodology

Based on the international methodological standards, the evolution of HLW/SF repositories in salt formations must be analyzed in terms of a safety case, which means an assessment of the total system performance (IAEA, 2008). In the US and Germany, site-specific concepts have been analyzed for salt domes (Gorleben site) and bedded salt formations–WIPP site and generic German sites (the KOSINA project, (Bollingerfehr et al., 2018)). Safety and safety demonstration concept for repositories in salt should take full credit of the favorable properties of salt formations. This concept is based on the safe containment of radioactive waste in a specific part of the host rock formation (the containment providing rock zone – CRZ), which comprises the geological barrier and the EBS, including the backfill (crushed salt or run-of-mine salt). The long term safety of the mine excavations will be ensured by the crushed salt. Crushed salt acquires its sealing capacity through compaction, driven by the convergence of the host rock. Convergence rate increases with heat produced from radioactive decay and increases with higher humidity and the water content in the rock. After several thousand years, it is expected the crushed salt will reach the same mechanical and hydraulic properties as undisturbed rock salt. Until this time, the EBS ensures the confinement of the disposed waste.

The methodology presented in this report was developed within the RANGERS project and serves as the base for the detailed integrity and performance assessment of the EBS. It summarizes the main aspects to consider during the design, the integrity assessment of the EBS, and the treatment of the EBS in the integrated total performance assessment. It comprises elements of the regulatory framework from which a safety concept is developed for a given geological site. This is the basis for the development of a repository concept and a sealing concept for the selected geological site. The evolution of the resulting repository system can be analyzed by utilizing a standardized FEP catalog that describes all features characterizing the system and all processes and events occurring during future evolution. The abstraction of the developed scenarios into modeling cases are the basis for the numerical based integrity assessment and performance assessment Kuhlman et al. (2024).

Maintaining the integrity of the repository system must be demonstrated for the reference scenario, the most probable evolution of the repository, as per EndlSiAnfV (2020). Less probable variant scenarios should be considered within the framework of the radiological long-term assessment, according to EndlSiAnfV (2020). Any alteration of the barrier effect must then be taken into account in the radiological consequence analysis. The proposed methodology extends this requirement to the integrity assessment of the repository system. This is because the analysis of alternative scenarios provides essential insights into the robustness of the repository system and can be used to optimize it (i.e., considering role of different safety functions). This has been already acknowledged in integrity analysis methodology adopted in the preliminary safety assessment of the Gorleben site (Beuth et al., 2012). This methodology formally comprises two parts:

- Integrity demonstration: The integrity analysis for the reference scenario.
- Integrity evaluation: The integrity analysis for less likely repository evolutions.

Figure 3-1 illustrates a process diagram for the integrity analysis. In practice, the two parts of the integrity analysis are indistinguishable. They differ only in the consequences resulting

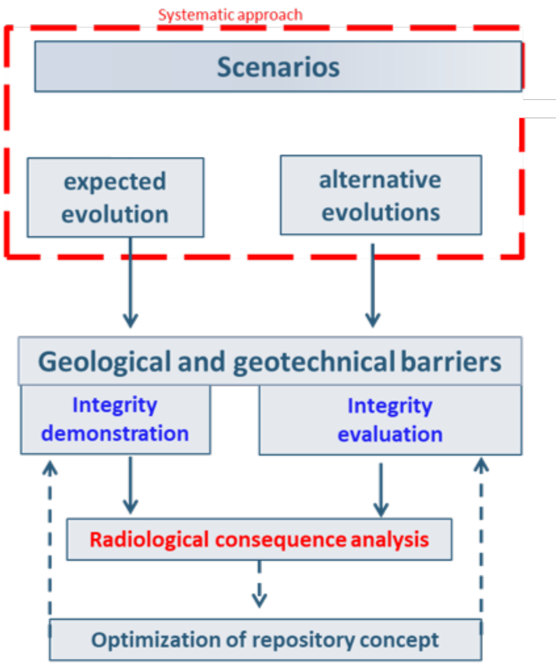


Figure 3-1: VSG concept for integrity assessment of geological and geotechnical barriers extract from Beuth et al. (2012)

from their analysis. The results of the integrity evaluation are further used in the analyses for the radiological long-term assessment and for determining the robustness of the repository system, while the results of the integrity demonstration analyses flow directly into the evaluation of whether the repository is meeting its ultimate objective of confining radioactive waste over the verification period. In the event that the integrity demonstration for the likely scenarios cannot be established, the safety requirements are not met. Then the repository concept and/or the site selection must be reexamined (Kock et al., 2012; Beuth et al., 2012).

The application of this approach in the proposed methodology allows a bifurcation in the process chain to assess the integrity of the EBS by examining in one branch the integrity demonstration for the reference scenario and in another branch, the integrity evaluation is carried out in closed interaction with the integrated performance and radiological assessment of the repository system. This step is carried out by means of comprehensive and specific numerical analyses of the behavior of the EBS under thermal-hydrological-mechanical and chemical (THMC) conditions. The link between the two kinds of assessment plays a key role in the optimization of the EBS.

The integrity demonstration of the EBS focuses on the sealing function and consists of several specific lines of evidence. It includes for sealing function the hydraulic resistances of the EBS, contact zone, and excavation disturbed zone (EDZ). Evaluation the structural integrity of EBS includes the structural stability, crack limitation, deformation limitation, (if applicable) filtration stability, and chemical/ mineralogical long-term stability. Because the EBS is an engineered structure, the procedure for the design and integrity demonstration of the EBS can rely on adequate regulations or recommendations in engineering. In Germany, the EBS is seen as structures of civil engineering and their adequate design has to be verified by a technical functional proof in accordance with EUROCODE (national implementation by DIN-EN-1997-1

(DIN EN 1997, 2014), DIN-EN-1990 (DIN EN 1990, 2010)) (Müller-Hoeppe et al., 2012b,a). In the USA, the national engineering code requirements such as ACI 318-14 (2014) for structural Concrete can be considered for the design of the EBS in compliance with other state specific regulations. The aim is to verify the required level of reliability of EBS construction.

The methodological approach bases on the concept of ultimate limit states in combination with the partial safety factor method. Therefore, the quantitative values of actions (i.e., impacts) or loads that may impair a structure's safety function are compared with the value of the structure-specific load resistances. With regard to construction integrity it is necessary that the load resistance is higher than the impacts. If the ultimate limit state is exceeded, the construction fails. For geotechnical barriers, ultimate limit states (e.g. cracking and deformation) can be described by crack limits (e.g., material specific fracture strength and dilatancy), deformation limits (e.g., volume and shear deformations) and tension limits (e.g., fluid pressure criterion).

The objective of the partial safety factor method is to cover uncertainties, for example, variations of representative values and modeling inaccuracies. For application of this method the values of the impacts or loads and the load resistances are multiplied by safety factors. The load resistances depend on construction material properties and the outline design of the EBS. The load resistances and the ultimate limit states are specific for a selected EBS design.

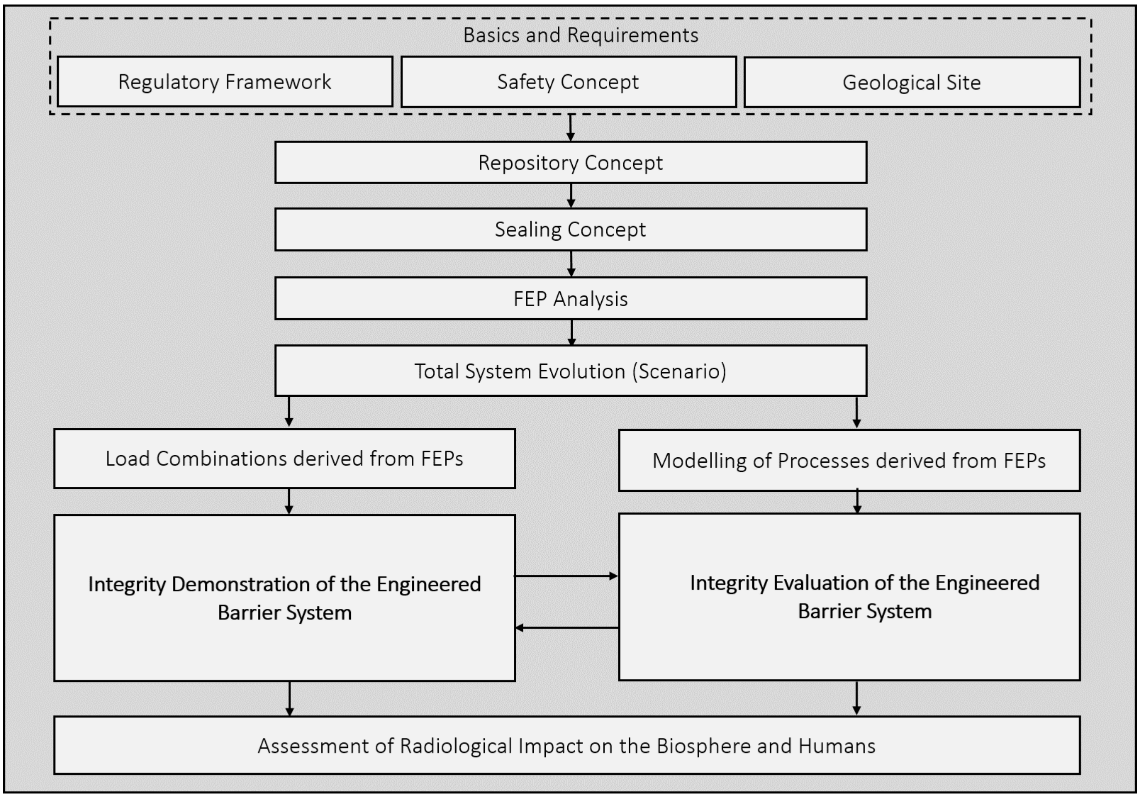


Figure 3-2: RANGERS methodology diagram for the design, integrity and performance of the engineered barrier system (EBS) in a salt repository

The EBS will be dimensioned according to technical regulations although their functional lifetime exceeds the usual functional lifetime of conventional structures in civil engineering (50 to 100 y) significantly. In order to extend the verification far beyond the conventional time of the engineering structure, one can rely on materials with proven long-term stability that can be demonstrated by natural analogues. It is also important to take into account the corrosion and alteration of the geomaterials in the design and verification process. Therefore, the chemical/mineralogical long-term stability of the EBS in contact with corrosive infiltrating waters must also be shown.

In the same way hydraulic resistance of the EBS can be verified. For the integrity assessment, the contact zone to the surrounding rock as well as the excavation damaged zone have to be considered beside the constructed barrier itself.

The integrity evaluation of the EBS focuses on the hydraulic evolution of the EBS for the alternative scenarios identified that affect the EBS. During this analysis, the EBS sealing function under altered conditions is analyzed and metrics can be derived from this analyses to optimize the EBS and to increase its robustness. For the integrity evaluation, no mechanical analyses are considered. This is the scope of the integrity demonstration. The integrity evaluation is intrinsically connected with the integrated performance assessment of the repository because the process involved in the alternative scenarios affect the radiological evolution of the repository system. Depending on the modeling approach, the integrity evaluation can be treated in the scope of the performance assessment of the repository system. These two assessments are therefore combined in the proposed methodology.

Figure 3-2 gives an overview of the proposed methodology. The components of the proposed methodology will be described in the following chapters.

4 Prerequisites

4.1 Regulatory framework

The national statutory and sub-statutory regulations establish the essential framework for the disposal of radioactive waste.

In Germany, these include, among others, the Atomic Energy Act (AtG 10), the Radiation Protection Ordinance (STV 08), and the Federal Mining Act (BBG 09) with its associated Federal Mining Ordinance (ABV 09) and especially the The StandAG, or Standortauswahlgesetz, which is the German law on the selection of repository sites for the disposal of radioactive waste (StandAG (2023)).

The StandAG (2023) empowers the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMUV) to establish safety requirements for final disposal (§ 26(3) StandAG) and requirements for conducting preliminary safety investigations (§ 27(6) StandAG) through regulations based on these safety principles. Based on these authorizations, the "Regulation on Safety Requirements and Preliminary Safety Investigations for the Final Disposal of High-Level Radioactive Waste" was published in October 2020. It includes the "Regulation on Safety Requirements for the Final Disposal of High-Level Radioactive Waste" (Endlagersicherheitsanforderungsverordnung – EndlSiAnfV) (EndlSiAnfV, 2020) and the regulation on requirements for conducting preliminary safety investigations in the site selection process for the final disposal of high-level radioactive waste (Regulation on Preliminary Safety Investigations for Final Disposal - EndlSiUntV)(EndlSiUntV, 2020) BGE (2022a).

Additionally, the relevant international recommendations from the International Commission on Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA) (2011), and the OECD Nuclear Energy Agency (2004) must also be considered, especially in terms of providing supplementary or detailed guidance to the national regulations. The International Atomic Energy Agency (IAEA) (2011) has been formulated for all types of repositories, including near-surface ones. More specific requirements for a deep geological repository can be found in International Atomic Energy Agency (IAEA) (2006) (Mönig et al., 2012).

In the US, the safety standards and regulations play a crucial role in evaluating the safety of a conceptual geologic repository for high-level radioactive waste (HLW) and spent nuclear fuel (SNF) managed by the US Department of Energy (DOE). The specific regulations from the US Environmental Protection Agency (EPA) and the US Nuclear Regulatory Commission (NRC), namely 40 CFR 197 (U.S. Environmental Protection Agency, 2001) and 10 CFR 63 (U.S. Nuclear Regulatory Commission, 2001) for Yucca Mountain, are not applicable to a separate DOE HLW/SNF repository. However, the existing EPA and NRC regulations for geologic repositories still remain in effect, as outlined in 40 CFR 191 (U.S. Environmental Protection Agency, 1985) and 10 CFR 60 (U.S. Nuclear Regulatory Commission, 1983), which govern the disposal of high-level radioactive waste (MacKinnon et al., 2012).

Nevertheless, these existing regulations may be replaced for a future DOE HLW/SNF repository (they were developed almost 30 years ago), to enhance consistency with the more contemporary approach to regulating geologic repositories, which emphasizes a risk-informed, performance-based methodology in (U.S. Nuclear Regulatory Commission, 2004), similar to the site-specific regulations for Yucca Mountain. Despite the uncertainty surrounding specific future safety standards, a robust safety case can still be constructed based on the existing standards (40 CFR 191 and 10 CFR 60) or on generic standards that incorporate internationally recognized dose or risk metrics important for establishing repository safety (MacKinnon et al., 2012) .

If the DOE decides to pursue the development of a deep geologic repository for DOE-managed HLW and SNF, additional requirements, such as those outlined in the National Environmental Policy Act (NEPA) (U.S. Congress, 1969) and 40 CFR 1500–1508 (Council on Environmental Quality, 1978), would need to be fulfilled. An Environmental Impact Statement (EIS) (of Energy, 1980) mandated by NEPA for any future new repository in the Delaware Basin could potentially leverage the EIS prepared for the Waste Isolation Pilot Plant (WIPP) (U.S. Department of Energy (DOE), 1997) and the technical foundation established in the present study (MacKinnon et al., 2012).

Lastly, the WIPP Land Withdrawal Act, Public Law 102–579 (U.S. Congress, 1992) as amended by Public Law 104–201, Section 12 (U.S. Congress, 1996), prohibits the disposal of HLW or SNF at the WIPP site (only defense-generated transuranic waste is licensed for disposal at WIPP). However, the extensive presence of Salado bedded salts in the Delaware Basin of southeast New Mexico and western Texas suggests that much of the technical basis developed for the WIPP site could be applied to other potential salt repository sites in the same region (MacKinnon et al., 2012).

4.2 Safety concept

The safety concept describes, through verbal and argumentative means, how the combination of natural conditions, technical measures, and ongoing processes collectively contribute to achieving safety in the technical sense (Mönig et al., 2012). It reflects the fundamental strategy to achieve the goals of concentration, isolation, and secure confinement of radioactive waste BGE (2022b).

In Germany, the basis for the development of a safety concept within the framework of the licensing documents is anchored in the StandAG where the fundamental safety requirements are defined. It is given as:

- *The radioactive and other pollutants in the waste must be concentrated and securely contained within a confinement-effective rock zone or, in accordance with § 23 (1) in conjunction with (4), within these barriers mainly based on technical and geotechnical barriers, with the aim of keeping these substances away from the biosphere. For a period of one million years, it must be ensured, with regard to the protection of humans and, to the extent it concerns the long-term protection of human health, the environment, that exposures due to releases of radioactive substances from the repository are negligible compared to natural radiation exposure.*
- *It must be ensured that the impacts of final disposal on humans and the environment abroad are no greater than permissible in the country.*
- *It must be ensured that, during the operational phase, the possibility of retrieval of the emplaced waste exists, and that sufficient provisions are made for potential recovery of the waste for a period of 500 years after the intended closure of the repository.*

- *The repository must be designed and operated in such a way that no interventions or maintenance work are required for reliable long-term containment of the radioactive waste in the post-closure phase."*

The EndlSiAnfV elaborates on these fundamental requirements outlined in the StandAG and specifies the requirements for formulating a safety concept. Section § 10 of the EndlSiAnfV states:

- *(1) In a safety concept, it must be demonstrated how the objective of concentrating and securely containing the radioactive waste according to § 4 paragraph 1 is to be achieved. The entire repository system, including its construction, operation, decommissioning, and the assessment period, must be taken into account.*
- *(2) The expected developments of the repository system during the assessment period form the basis for the development of the safety concept. Deviating developments must be considered.*
- *(3) The safety concept must consider the results of the comprehensive preliminary safety investigation according to § 18 paragraph 1 sentence 2 of the Site Selection Act. In particular, changes compared to the preliminary safety concept based on the comprehensive preliminary safety investigation must be indicated and justified.*
- *(4) It must be demonstrated that the optimization of the safety concept according to § 12 paragraph 2 has been completed.*
- *(5) The safety concept must include a representation of all planned barriers of the repository system, in particular the essential barriers according to § 4 paragraph 3, their respective safety functions, and their interaction. The representation must also include a closure concept for sealing cavities that have been loaded with radioactive waste. It must be shown that the safety functions of the repository system and its barriers are insensitive to internal and external influences and disturbances, and that the behavior of the barriers is well predictable.*
- *(6) The safety concept must also include: 1. a schedule for the construction, operation, and decommissioning of the repository, demonstrating how the safety of the repository according to § 17 can be ensured and how the radioactive waste can be maintained in a safe condition, 2. a representation of the measures ensuring the retrievability of the emplaced radioactive waste until the start of decommissioning according to § 13, and 3. a representation of the provisions made to enable the recovery of the emplaced radioactive waste according to § 14.*
- *(7) The safety concept must take into account measures necessary until the completion of decommissioning, 1. to ensure the necessary protection of the repository from interference and other influences by third parties, and 2. for the monitoring of nuclear material.*

BGE (2022a) as the implementer in Germany summarizes the basic safety requirements for a repository system regulated in the StandAG and the EndlSiAnfV as follows:

- *The assessment period is one million years from the intended closure of the repository" (§ 3 (1) EndlSiAnfV).*
- *Future developments of the repository system and the geological situation at the repository site must be considered during the assessment period (§ 3 (2) EndlSiAnfV).*
- *The intended repository system must ensure the secure containment of radioactive waste passively and maintenance-free through a robust, tiered system of various barriers with different safety functions" (§ 4 (2) EndlSiAnfV).*
- *All underground cavities must be excavated in a geologically benign manner and subsequently closed in a way that preserves the relevant properties of the barriers necessary for the secure containment of radioactive waste (§ 9 (2) EndlSiAnfV), and they must be limited to an unavoidable extent (§ 11 (4) EndlSiAnfV).*
- *The preliminary safety investigations must comply with the state of science and technology (§ 27 (2) StandAG).*
- *The disposal casks emplaced in the repository must be retrievable until the start of decommissioning of the repository (§ 13 (1) EndlSiAnfV).*
- *Sufficient provisions must be made to enable the recovery of the emplaced repository packages during decommissioning and for a period of 500 years after the intended closure of the repository (§ 14 (1) EndlSiAnfV).*
- *Regarding operational safety, the operation must have been successfully tested in advance (§ 16 (1) EndlSiAnfV), and the relevant plant conditions for*

Furthermore, the following safety requirements exist regarding the achievement of the protection objectives of concentration and secure containment, as well as exposure. These requirements are to be examined based on criteria specified in the EndlSiAnfV and in the long-term safety analysis (BGE, 2022a):

- *Compliance with limits regarding the mass and quantity of substances released from the essential barriers of the repository system (§ 4(5) EndlSiAnfV).*
- *Demonstration of the integrity and robustness of the essential barriers, as well as the robustness of additional barriers (§§ 5 and 6 EndlSiAnfV).*
- *Estimation of radiation dose values throughout the assessment period (§ 7 EndlSiAnfV).*
- *Prevention of self-sustaining chain reactions (§ 8 EndlSiAnfV).*

In order to ensure compliance with the aforementioned safety requirements, it is necessary to formulate measures within the repository concept, sealing concept, and verification concept. Within the scope of the VSG project, various measures pertaining to the sealing concept have been developed. Although these measures were initially based on outdated safety requirements of the BMU ((BMU, 2010)), they remain valid for the new safety requirements of the EndlSiAnfV. These measures provide the framework for the development of the sealing concept and will be presented in the relevant section dedicated to the sealing concept. It should be noted that the following presentation of measures is not exhaustive.

4.3 Geological site

The geological conditions of the site form the primary constraints for the repository and the delineation of the mine layout. Both Germany and the United States are in the nascent phases of their site selection procedures (MacKinnon et al., 2012; BGE, 2022b), indicating that there is not a specific site or rock type under specific scrutiny that could guide the further elaboration of the repository concept. During the site selection phase, preliminary site explorations, encompassing deep drilling or mining excavation, will yield an array of technical data such as geological, hydrological, geochemical, geophysical, and thermal-mechanical data from the potential sites (MacKinnon et al., 2012; BGE, 2022b).

At this stage, one leans on prior research projects to comprehend the characteristics of the salt geological formations. From the available geological exploration data available in Germany, a representative overall geological situation with a synthesized sequence of layers was created for the generic considerations in the KOSINA project (Völkner et al., 2017a). This will serve to illustrate the proposed methodology.

4.3.1 Salt formations in USA

The main historical survey and nation-wide inventories of salt formations in the contiguous United States was conducted in the 1960s Pierce and Rich (1962) and 1970s Johnson and Gonzales (1978). These efforts started with high-level studies of the regions with bedded and domal salt formations at appropriate depths for a radioactive waste repository (Figure 4-1). It was noted that salt deposits are "widely distributed" in 24 of the 50 states Pierce and Rich (1962).

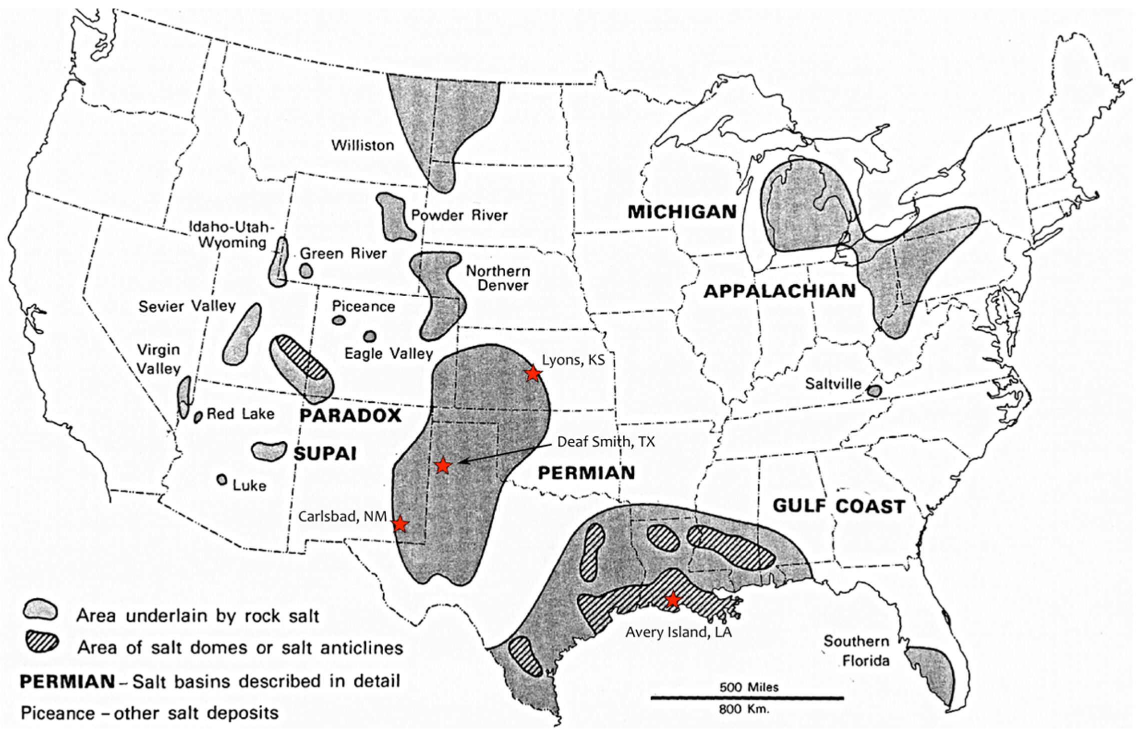


Figure 4-1: Map of bedded and domal salt deposits in the United States (Kuhlman et al., 2012; Johnson and Gonzales, 1978).

These studies were done in response to initial investigations by the US National Academy of Sciences into the concept of radioactive waste disposal that indicated disposal in salt formations would likely be feasible and would be worth pursuing further investigations Hess et al. (2057); Lomenick (1996).

There have been several more detailed historical investigations into locations for disposal in salt, including bedded and domal salt sites (see red stars in Figure 4-1). The bedded salt of the Permian Basin underlies several states (New Mexico, Texas, Oklahoma, Colorado, and Kansas – Figure 4-2), and has been the subject of three separate salt repository investigations Kuhlman et al. (2012).

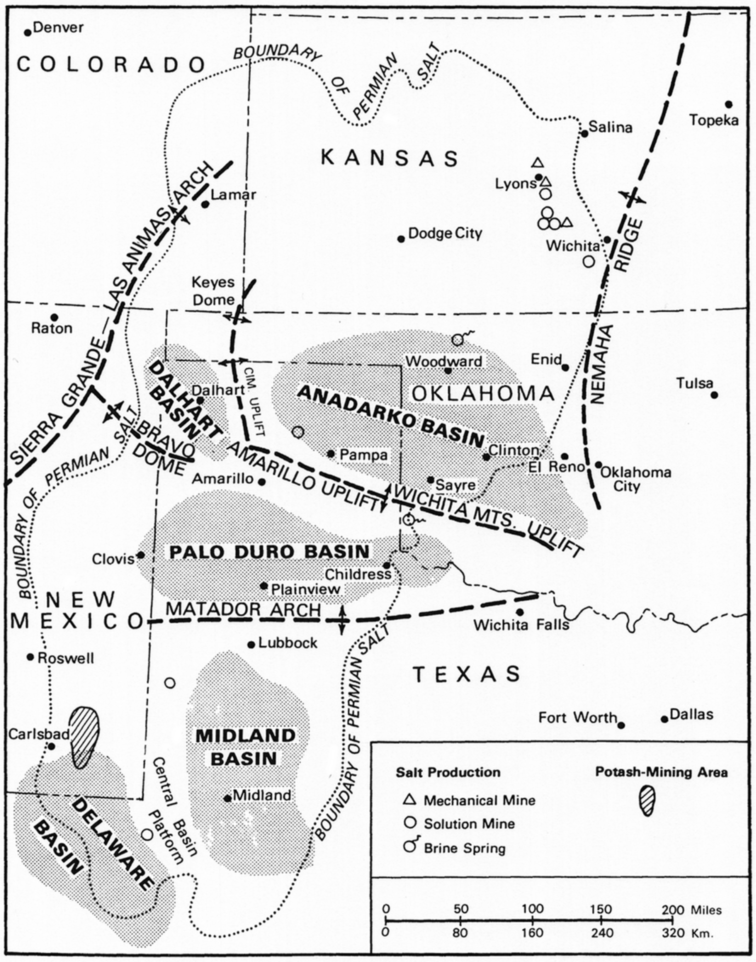


Figure 4-2: Distribution of sub-basins within larger Permian Basin Johnson and Gonzales (1978)

In in the 1960s in Lyons Kansas (Figure 4-2), Project Salt Vault Bradshaw and McClain (1971) utilized a bedded salt mine as an underground research laboratory, with the initial expectation that the facility could be used for disposal after the initial investigation. Due to local opposition to the project and unanswered questions about solution mining activities in the area, the investigation moved on to salt sites elsewhere Lomenick (1996).

By the mid-1970s, the site selection process then turned its focus to bedded salt of the Delaware basin (Figure 4-2) in southeastern New Mexico Kuhlman et al. (2012). After the initial site investigation into the Salado formation with boreholes in the late 1970s Powers et al. (1978), the first excavations that would become WIPP began in the early 1980s of Energy (1980). During construction, the licensing process was still being finalized, and the details of the exact mission for the WIPP site continued to change until the Land Withdrawal Act U.S. Congress (1992, 1996) (no spent fuel or high-level waste at WIPP, only defense-generated transuranic waste). After approval form the US EPA and New Mexico Environment Department (NMED), WIPP accepted its first shipment of transuranic waste in 1999.

A series of drif-scale thermal/mechanical demonstration experiments were conducted at WIPP (Matalucci, 1987) for a future salt-based site for heat-generating waste, which located in bedded salt of Palo Duro Basin (Figure 4-2) in Deaf Smith County, Texas of Civilian Radioactive Waste Management (1988). This site was investigated from the surface through boreholes, but was abandoned by 1987 when Yucca Mountain was picked by law to be the final destination for high-level waste and spent fuel in the United States Lomenick (1996).

From the late 1970s into the 1980s, underground research laboratory experiments relevant to radioactive waste disposal were conducted in a mine at the salt dome at Avery Island, Louisiana ave (1980); Kuhlman et al. (2012). This location was never seriously considered for disposal, but is characteristic of the numerous salt domes in the US Gulf Coast, which evolved in a manner characterized by Figure 4-3.

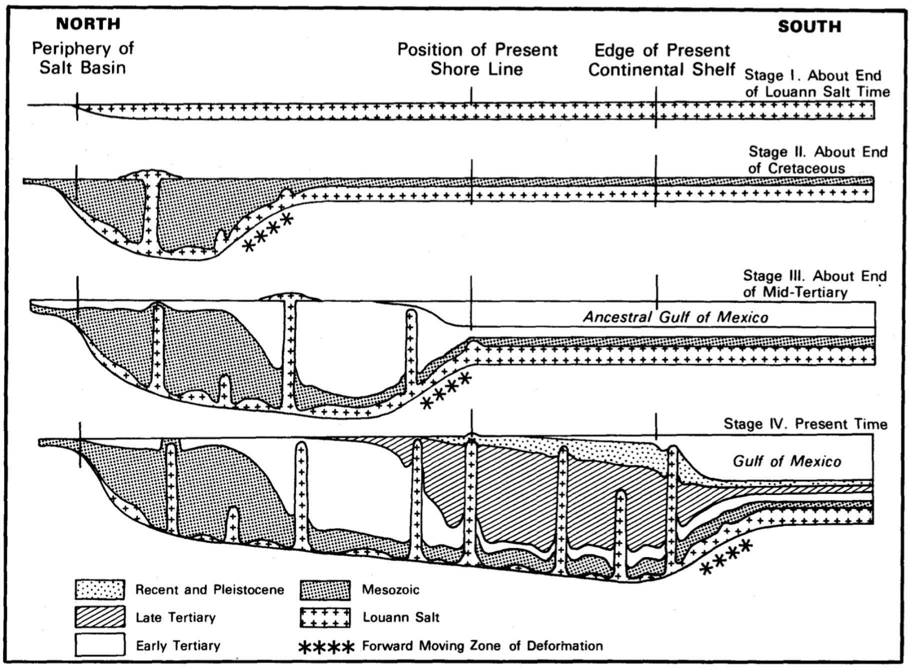


Figure 4-3: Evolution of domal salt in the US Gulf Coast Johnson and Gonzales (1978)

Additional investigations were performed in other sedimentary basins (e.g., Michigan, Appalachian, and Williston basins – Figure 4-1), but no significant site characterization activities were performed related to radioactive waste disposal Lomenick (1996). Other salt domes in the Gulf Coast and a salt anticline (i.e., Paradox Basin) were briefly investigated, but no significant site activities were conducted.

4.3.2 Salt formations in Germany

Salt formations comprise a sequence of sediment rocks that originate from the repeated evaporation of water in ocean basins in arid climate. At first, fine clastic sediments settled down. These were followed with increasing salinity by carbonates, then sulfates and eventually chlorides that formed and sank to the basins floor. The repetition of this cycle led to the accumulation of layered salt formations with combined thicknesses of up to a few hundred meters according to picture a of figure (4-4). Based on the comparatively low density of salt and its ability to creep, in some cases the older and more mobile salt started to migrate towards the surface. Simultaneously salt from the surrounding area migrated towards the center, leading to even thicker salt accumulations with higher geological complexity that are called salt pillows according to picture b of figure (4-4). Because of the upward movement, the covering sediment layers were stretched and thinned. As the uplift continued and the deposit matured the angle of the salt flanks increased, leading to ruptures in the covering layers and eventually forming a salt dome according to picture of figure (4-4). These deposits often show considerable micro-folding of the salt layers, leading to a complex geology.

Rock salt in Germany has been deposited in several sequences, which formed lithostratigraphic groups. From the oldest to the youngest one, these groups are called: Rotliegend, Zechstein, Röt, Muschelkalk, Keuper, Malm and Tertiary. Only the Zechstein- and in special cases the Malm-Salinar seem potentially suitable to host a repository according to regulatory requirements (Reinhold et al., 2014). As the Malm-Salinar consists of interbedded salt-clay and anhydrite layers and occurs in extremely localized successions, further investigation and definition of the boundaries are required before generic models can be built (Reinhold et al., 2014). According to the InSpEE project that elaborated the distribution and geological properties of the salt structures occurring in Germany (von Goerne et al., 2016), the genesis of pillow salt structures is mainly influenced by rock salt deposits of one stratigraphic unit (e.g. Zechstein). In exceptional cases, two evaporitic sequences of different ages can also be involved in the genesis of the salt pillow but in Germany these structures usually lie at depths greater than 2000 m below sea level (Gast and Riesenberg, 2016; Pollok et al., 2016). Therefore only the Zechstein-Salinar is converted into a generic geological model here. The Zechstein-Salinar is divided into the seven formations from bottom to top: Werra, Stassfurt, Leine, Aller, Ohre, Friesland and Fulda. Werra, Stassfurt and Leine are generally the thickest layers, while others only accumulate to a few tens of meters. Each formation is introduced by basal fine clastic sedimentation, followed by carbonates and evaporites. The evaporites sub-sequence is based on the order of precipitation. From bottom to top anhydrite, rock salt, potash and magnesia salts can be found. Due to local settings the thickness of each layer can vary considerably. The base of the rock salt layers in the south of the former North German Basin begins at a depth of several hundred meters and drops down to more than 5,000 m in its center. Favorable deposition zones in Germany are therefore found at the south parts of the North German Basin. The most promising basins are shown in Figure 4-5.

4.3.3 Description of a generic salt pillow geological model

As Germany has not yet selected a geological site for a final waste disposal this case study uses a generalized data set of a salt pillow that represents the basic properties of the most promising basins. The geological settings between single sites in these regions will differ from each other, but as they are linked to the same deposition and formation process their behavior can, to a certain extent, be described with a generic model. Such a model represents

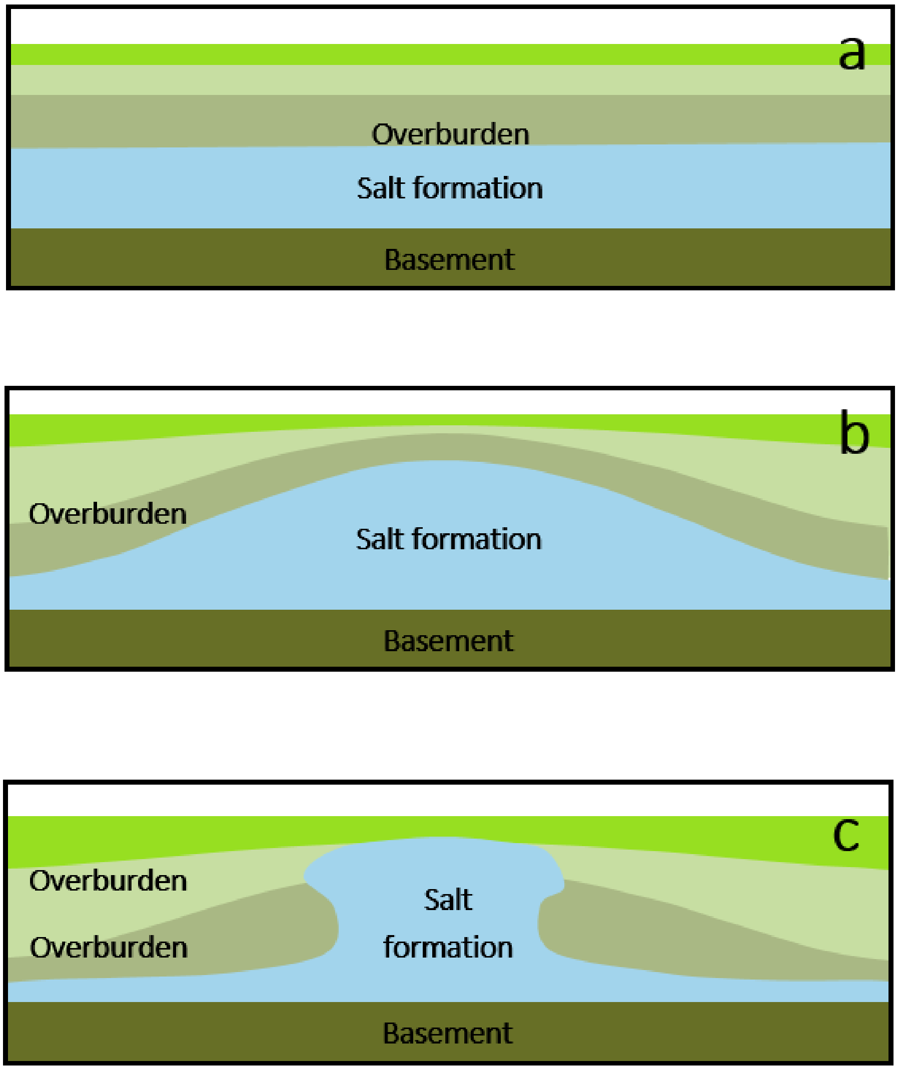


Figure 4-4: a. Schematic diagram of a flat bedded salt after Völkner et al. (2017a), b. Schematic diagram of a salt pillow after Völkner et al. (2017a) and c. Schematic diagram of a salt dome after Klinge et al. (2007)

the fundamentals of multiple example sites and by that, allows the application of common technical measures.

In order to create the generic geology, at first the real lithology of reference areas (Reinhold et al., 2014), is used to derive a synthetic sequence of layers for the Stassfurt (z2) and Leine (z3) formations of the Zechstein evaporites (Völkner et al., 2017a). Supplementary regional-geological information on the sedimentary sequence help to add underlying rocks and sedimentary layers on top of the Leine-Formation (Bollingerfehr et al., 2018). With this method a total of 18 regionally well characterizable lithostratigraphic units, abbreviated with small letters and numbers, were defined. To optimize the computing times of the generic geological 3D model, several layers with similar geomechanical properties were then bundled to a total of 12 homogeneous zones, abbreviated with capital letters and numbers. Figure 4-6 summarizes the lithostratigraphic units and the related homogeneous zones taken from the project KOSINA (Bollingerfehr et al., 2018) that build the lithology of the salt pillow.

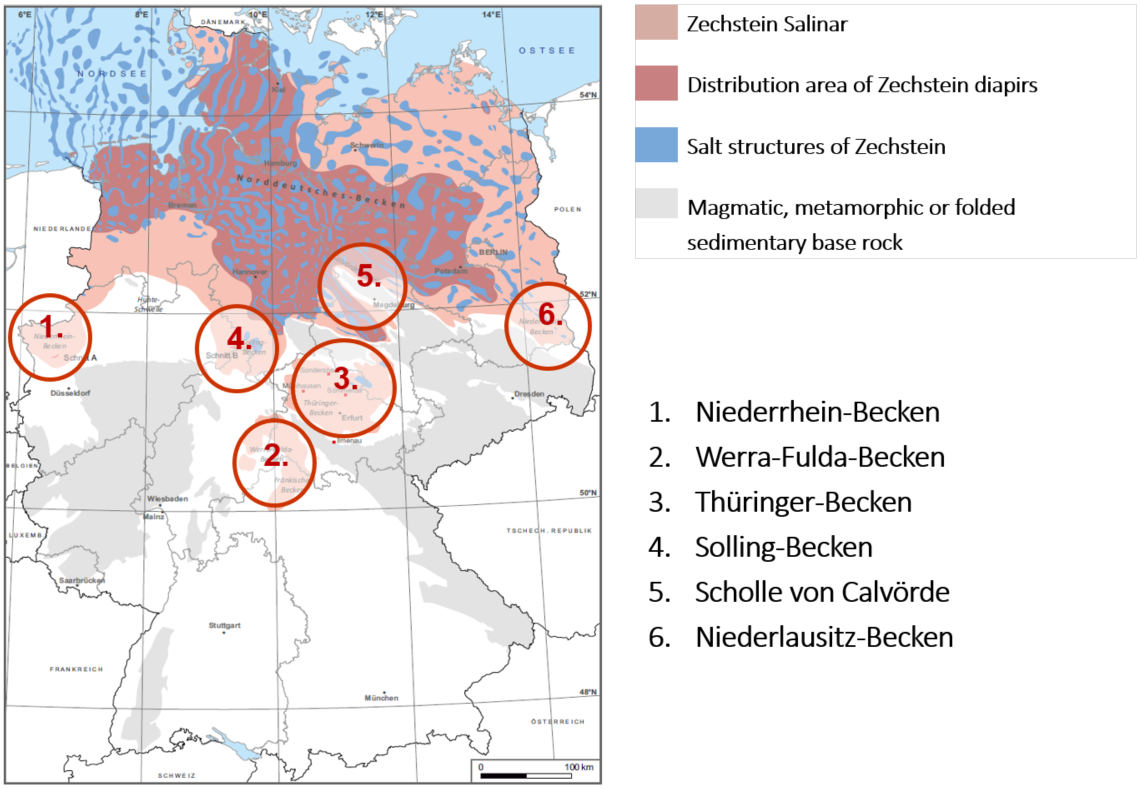


Figure 4-5: Schematic distribution of Zechstein salt formations in Germany, modified after Reinhold et al. (2014)

Following, a literature review of homogeneous geological salt layers including appropriate constitutive models as well as thermal, mechanical and hydraulic parameters of geological homogeneous layers was conducted in KOSINA (Liu et al., 2017) to provide the model input data. Table 4-1 summarizes material parameters used for the numerical model calculations for the bedded salt formations, the overburden and the basement rocks.

In the thermo-mechanical calculations, the lithostatic pressure gradient for all layers is set to 0.022 MN/m³ and the thermal conductivity for the salt formations excluding potash seam and main anhydrite is a parameter dependent on temperature (Bollingerfehr et al., 2018).

The generic geological model of the salt pillow from the KOSINA project is located on the southern crest of the North German Basin. This area is geomorphologically influenced by ground and end moraines of the Elster and Saale glacial stages with a topography of 45 m - 75 m above sea level (Völkner et al., 2017a). To create a typical setting of such a region the aforementioned 18 lithostratigraphic layers were assigned thicknesses according to Figure 4-7 and a general dip of 5° to 7° of the top of the Stassfurt rock salt was defined. Based on this information, the 12.5 km long reference profile AA' with an E-W orientation as well as three additional approximately 10 km long profiles (BB', CC', DD') that intersect perpendicular with a N-S orientation were designed (Völkner et al., 2017a).

Within these reference profiles the upper boundary of the Stassfurt rock salt that should host the repository ranges from 460 m – 1,045 m below ground level (bgl) and with its thickness of 150 m to 600 m the lower boundary varies between 670 m and 1,220 m below ground level

	regionally well characterizable lithostratigraphic units		Homogenous zones in the computing model	
Overburden	q	Quaternary	Q	
	t	Tertiary	T	
	sm	Middle Bunter	S	
	su	Lower Bunter		
Ohre-formation	z5	Ohre sediments		Host rock
Aller-formation	z4NA	Aller rock salt	NA4	
	z4RT-z4PA	Roter Salzton/ Pegmatitanhydrit		
Leine-formation	z3SS-TM	Schwadensalz/ Tonmittelsalz	AM3	
	z3AM	Anhydritmittelsalz		
	z3RO	Ronnenberg potash seam	K3	
	z3NA	Leine rock salt	NA3	
	z3HA	Main Anhydrite	A3	
	z3GT	Grauer Salzton		
Stassfurt-formation	z2SF	Stassfurt potash seam	K2	
	z2NA	Staßfurt rock salt EMPLACEMENT HORIZON	NA2	
Underlying rocks	z2BA	Basalanhydrit	A2/C2	
	z2SK	Staßfurt-Carbonate		
	ro	Rotliegend	R	

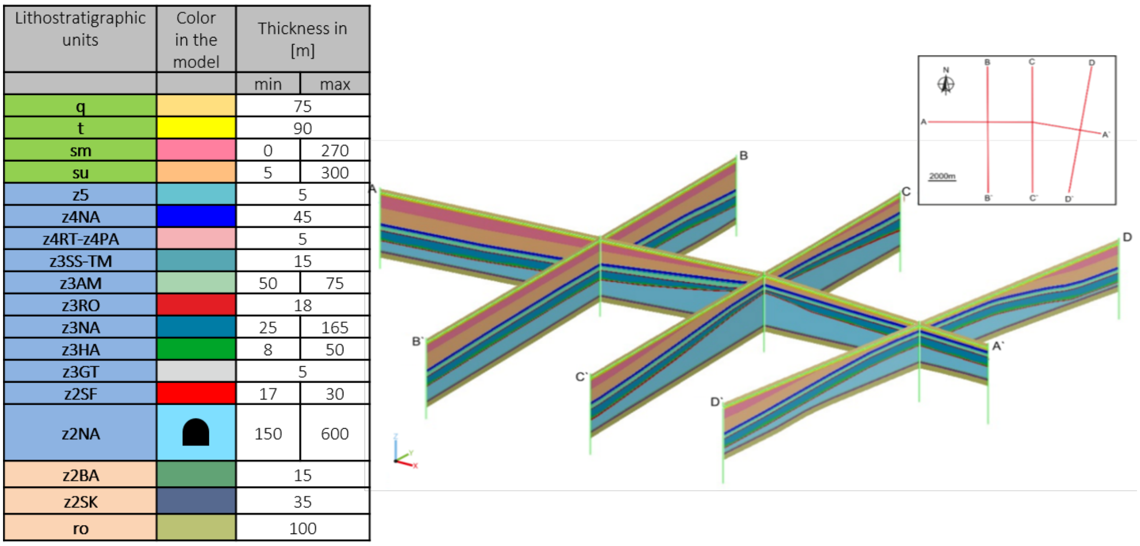
Figure 4-6: Generalized standard profile of North German salt formation composed of well charactierizable lithostratigraphic units that are grouped to homogenous layers, after Bollinger-fehr et al. (2018)

(see: Table 4-7 being part of figure 4-7). The greatest thickness of the salt pillow is reached at the intersection of profile AA' and CC'. It can be observed that on top of the crest of the pillow the overburden layers have been eroded, while towards the ends of the profiles their thickness increases considerably (Völkner et al., 2017a).

The thickness of the cover rock consisting of lithostratigraphical units Q, T, sm and su, varies in the model area between approximately 800 m in the west and approximately 140 m in

Table 4-1: Model parameters of homogeneous zones after Liu et al. (2017)

Zones	Symbol	ρ $\left[\frac{kg}{m^3}\right]$	λ $\left[\frac{W}{m \cdot K}\right]$	c_p $\left[\frac{J}{kg \cdot K}\right]$	α $\left[\frac{1}{K}\right]$	E [GPa]	ν [−]
Quaternary	Q	2000	2.3	950	$1.0 \cdot 10^{-5}$	0.1	0.33
Tertiary	T	2100	2.1	905	$1.0 \cdot 10^{-5}$	0.5	0.33
Bunter	S	2500	2.6	760	$1.0 \cdot 10^{-5}$	15	0.27
Aller rock salt	NA4	2235	5.2	860	$4.0 \cdot 10^{-5}$	25	0.27
Anhydritmittelsalz	AM3	2275	5	860	$3.5 \cdot 10^{-5}$	30	0.27
Potash seam Ronnenberg	K3	1850	1.5	903	$2.5 \cdot 10^{-5}$	16	0.26
Leine rock salt	NA3	2160	5.2	860	$4.0 \cdot 10^{-5}$	25	0.25
Main anhydrite	A3	2700	4.2	860	$1.6 \cdot 10^{-5}$	60	0.25
Potash seam Staßfurt	K2	1850	1.5	903	$2.5 \cdot 10^{-5}$	17	0.28
Staßfurt rock salt	NA2	2160	5.2	860	$4.0 \cdot 10^{-5}$	33	0.25
Anhydrite/carbonate	A2/C2	2700	4.2	860	$1.6 \cdot 10^{-5}$	30	0.27
Underlying red	R	2500	2.7	760	$1.0 \cdot 10^{-5}$	17	0.27



Lithostratigraphic units	Color in the model	Thickness in [m] min	max
q		75	
t		90	
sm		0	270
su		5	300
z5		5	
z4NA		45	
z4RT-z4PA		5	
z3SS-TM		15	
z3AM		50	75
z3RO		18	
z3NA		25	165
z3HA		8	50
z3GT		5	
z2SF		17	30
z2NA		150	600
z2BA		15	
z2SK		35	
ro		100	

Figure 4-7: Thickness of layers and generic geological profiles in the "salt pillow" model region

the east. The evaporitic host rock consisting of Stassfurt, Leine, Aller and Ohre formations, reaches a thickness of more than 800 m in the center of the salt pillow. No modeling of potentially existing cap rocks at the top of the salt was undertaken. Instead, the geological units overlying z2NA in the center of the salt pillow are strongly thinned and the Middle Bunter (sm) in particular is almost non-existent. Away from the salt pillow, however, sm reaches a thickness of more than 300 m at the western edge of the model area (Bollingerfehr et al., 2018). It is known that within the North German basin, there are numerous fault zones in the basement and overburden layers that lead NNE-SSW or that follow direction WNW-ESE up to NW-SE. Nonetheless, the model does not incorporate fault tectonics or salinar tectonics (Baldschun et al., 2001). The fault characteristics of the pre-saline horizons, as well as the fragmentation of the main anhydrite into blocks, are not part of the reference profile and thus not included in the 3D model based on the profile (Bollingerfehr et al., 2018).

Table 4-2: Vertical extension of the Stassfurt rock salt (z2NA) in the reference profile

	Min	Max
Depth of top	-390 m NN (460 m bgl.)	-975 m NN (1,045 m bgl.)
Depth of base	-600 m NN (670 m bgl.)	-1,150 m NN (1,220 m bgl.)
Thickness	150 m	600 m

The 3D-modelled area is based on the length of profile AA' and the width defined by profiles BB', CC' and DD'. Within the 3D-model (see Figure 4-8) the Stassfurt rock salt sequence which was selected as the emplacement horizon has a thickness of up to 600 m. This diminishes rapidly (<300 m) in the direction of the edges of the model, and even thins to below 100 m in the NE and SE. The base of the emplacement horizon (z2NA base) is approximately 600 m below sea level (bsl) (approximately 670 m bgl) in the east, and deepens in the NW to over 1,200 m bsl (>1,270 m bgl). The depth of the top (z2SF base) also decreases to the west (to >1,000 m bsl. The top of the emplacement horizon in the centre of the salt pillow is <400 m bsl. The dashed line marks a Stassfurt rock salt thickness of at least 300 m in all figures.

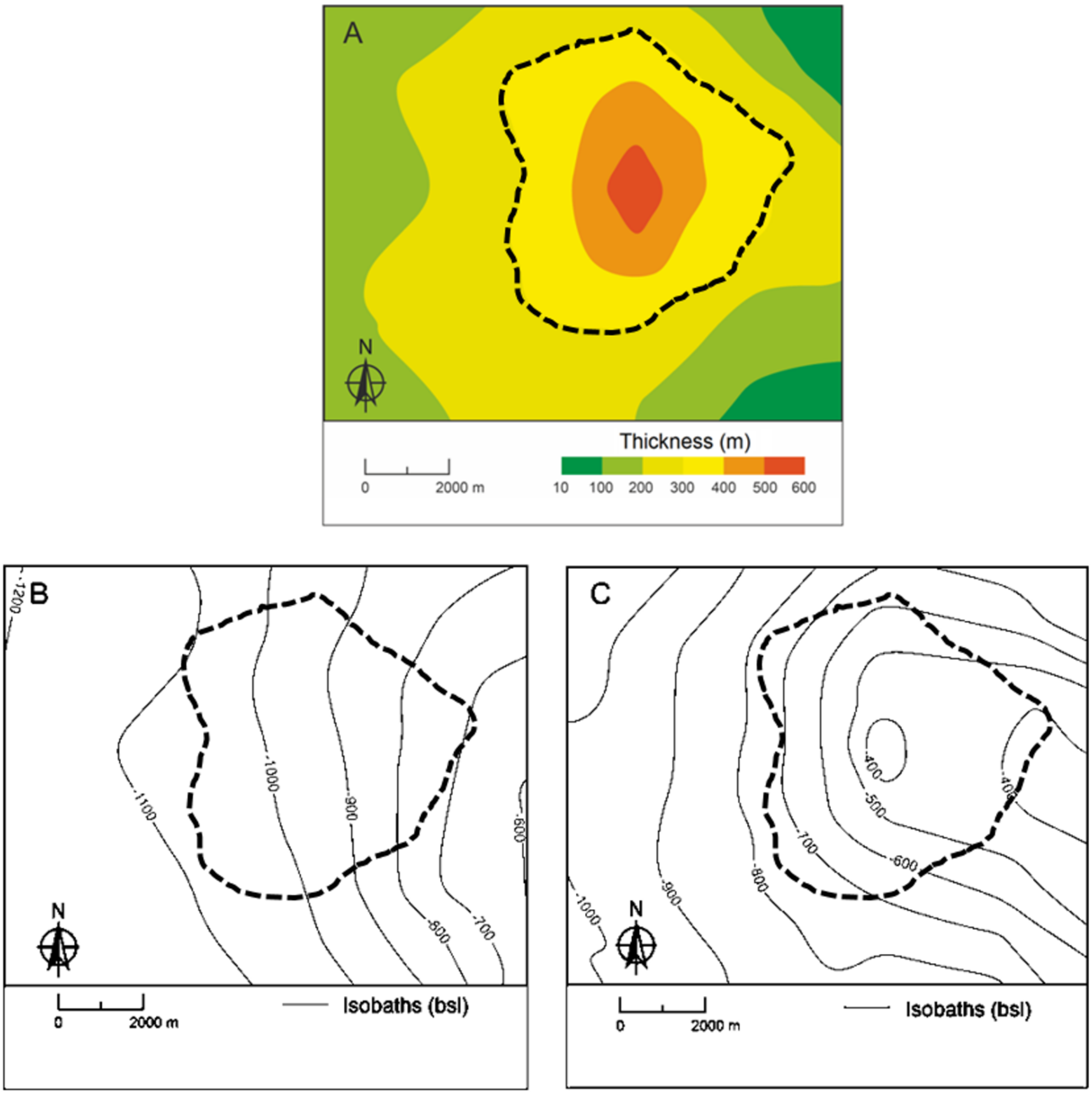


Figure 4-8: Thickness (A) and depth maps for base (B) and top (C) of the z2NA model unit in the “salt pillow” model type (Bollingerfehr et al., 2018)

5 Repository concept

5.1 Regulatory requirements

In salt, a repository concept has to be developed in accordance with the safety concept and the safety requirements. The safety requirements to be fullfiled by the repository concept in Germany have been explicitely addressed in paragraph § 11 of the EndlSiAnfV. Those requirements are (EndlSiAnfV, 2020, p. 7–8):

- *The technical design of the final repository must be derived and optimized from the safety concept.*
- *It must be demonstrated that the optimization of the design of the final repository according to § 12 paragraph 2 of the EndlSiAnfV is complete.*
- [...] *all results from the exploration of the final repository site, particularly the geological findings from the underground exploration, including their uncertainties and their relevance for the safety and robustness of the final repository system, must be taken into account.*
- *The violation of the geological formation and the containment-providing rock zone (CRZ) with shafts, excavations or drillings, must be restricted to the unavoidable extent for the safe construction, safe operation, and safe closure of the final repository.*
- *For all intended technical components of the final repository, the conditions for safe operation must be documented, justified, and taken into account in the design of the final repository.*

§ 11 of the EndlSiAnfV also requires that the repository concept should include the definition of the essential barriers as per § 4 paragraph 3 of EndlSiAnfV. It should include the location and dimensions of the CRZ. Additionally, the definition of the further barriers of the final repository system, taking into account the final repository packages, emplacement technology, and emplacement geometry, should be defined. The positioning and technical execution of all underground cavities, particularly areas intended for the emplacement of final repository packages, as well as all surface accesses, should be clarified. The specifications of the installations and machines used for handling the final repository packages must be detailed. An emplacement concept, particularly the arrangement and handling and control of the final repository packages, should be developed. Measures to ensure the retrievability of already emplaced final repository packages and the decommissioning measures including the closure measures, should be planned and implemented.

Additionally, design requirements and technical measures have been defined that altogether will ensure compliance with the objectives of the safety concept. The following requirements are related to the site selection procedure (StandAG, 2023):

- The construction of the repository will be done in a stable geologic region with characteristics that are well predictable for the demonstration period, e.g. no active fracture zones, no relevant seismic activity, very low salt diapirism and resulting subrosion.

- The disposal fields will be located at a depth that excludes any natural impairment of the CRZ from the surface, e.g. erosion of glacial channels. So, for northern Germany, a depth between 600 m and 800 m below sea level has been pursued.
- The thickness of the CRZ has to be 100 m at minimum.
- Due to the extremely low permeability of the undisturbed salt rock there is no relevant groundwater flow. Therefore the mass transport of radionuclides by advection will be comparable to that by diffusion.

For mine construction / operation the following requirements are defined:

- The mine workings of the repository are completely surrounded by host rock.
- The construction of disposal fields will be in a well-characterized salt formation with very low humidity and high plasticity (high creeping rates).
- The void volume to be excavated for the mine will be minimized, and excavation will be done by techniques that disturb the rock as little as possible.
- Loaded disposal fields will be backfilled and abandoned (operation in retreating mode).
- The halite layers of the salt formations have favorable properties to meet the containment function.

The halite layers have a very low permeability so that slow diffusion is the dominating process of mass transport and advection is of little relevance. Salt plasticity will seal any impairment of the rock due to mechanical impacts. Humidity in halite is very low. In the host rock surrounding the disposal areas, a CRZ will be defined that will not be affected by any impacts from the surface (e.g. ice ages) or evolutions of geosphere (e.g. fracture zones).

Several of the technical measures have the safety function to seal the unavoidable perforation of the geologic barrier rapidly and effectively. The long-term goal is to restore the host rock's integrity and to avoid evolutions that result in an impairment of the CRZ. In detail, the following technical measures are included:

- **Shaft seals, drift seals, borehole seals, and buffer:** To comply with their safety function, these barriers have a low integral permeability, which minimizes an advective solution flow. The integrity of these barriers has to be demonstrated for 50,000 years. For this period the development of hydrochemistry can be predicted (no glacial induced changes of hydrochemistry) and the compaction of the crushed salt backfill in the mine excavations has been finished.
- **Backfill:** The safety functions of the backfill comprise the stabilization of the excavations and the limitation of fluid flow. Backfilling will be done with crushed salt, that reaches similar mechanical and hydraulic properties like the surrounding salt formation after completion of compaction.
- **Temperature limit:** Temperature limits have been defined to avoid an alteration of the spent fuel elements and the glass matrix of the vitrified reprocessing waste and – in

combination with safety distances – the degradation of carnallite layers with low thermal stability

- **Disposal Canisters:** The disposal canisters will be designed to be retrievable during the operation period and to be manageable for 500 years after repository closure and they will be loaded in such a way that criticality can be excluded.

A penetration of the geologic barrier is inevitable during mine construction and will result in its local impairment. In the long term, creep processes promoted by the plastic properties of the salt host rock will lead to the closure of such mine openings. Thus, in the long term, the original properties of the geologic barrier will be restored. To overcome this period, engineered high-performance shaft and drift seals will be constructed, which will provide the required sealing immediately after installation. To guarantee the long-term sealing of the penetrations, the mine workings will be backfilled with crushed salt that is stable in the long term. Over time, the properties of this backfill will become similar to the surrounding host rock.

5.2 Repository concept development

5.2.1 Considered geological site – Determination of the available space

The geology around a nuclear waste repository has to provide conditions that allow a safe operation and secured containment. In order to separate conditions that are clearly not adequate from the ones that potentially are, StandAG (StandAG, 2023) defines preconditions for a nuclear repository in Germany. According to these documents a site will be excluded as geologically particularly unfavorable if any exclusion criteria is not fulfilled. In addition several minimum requirements are set to weight the overall suitability. All requirements defining the space around the repository and additionally qualitative aspects that were given in the preliminary safety analysis of the Gorleben site (Mönig et al., 2012) and that were quantified in the project KOSINA (Bollingerfehr et al., 2018) can be summarized as follows (See Figure 5-1):

1. The depth of the repository has to be between 500 m (600 m according to the safety concept) and 1,000 m below ground level.
2. The minimum distance between drifts or cavities to top and bottom of the rock salt layer is 50 m. The rock salt layer therefore needs to be thicker than 100 m.
3. There has to be a 500 m lateral safety pillar around the repository.
4. A minimum distance of 300 m between disposal rooms and shafts must be observed.

In order to determine the available space for a repository within the considered geology, the safety distances are applied. Based on the boundary positions the respective criteria separate the suitable from the unsuitable areas within the rock salt formation. Only those areas are considered for a repository layout that satisfy all requirements:

1. The generic geology offers a rock salt thickness of more than 100 m over the whole map section except the far southeast and northeast corner. Therefore the layer offers enough distance for the repository towards the upper and lower boundary of the rock salt.

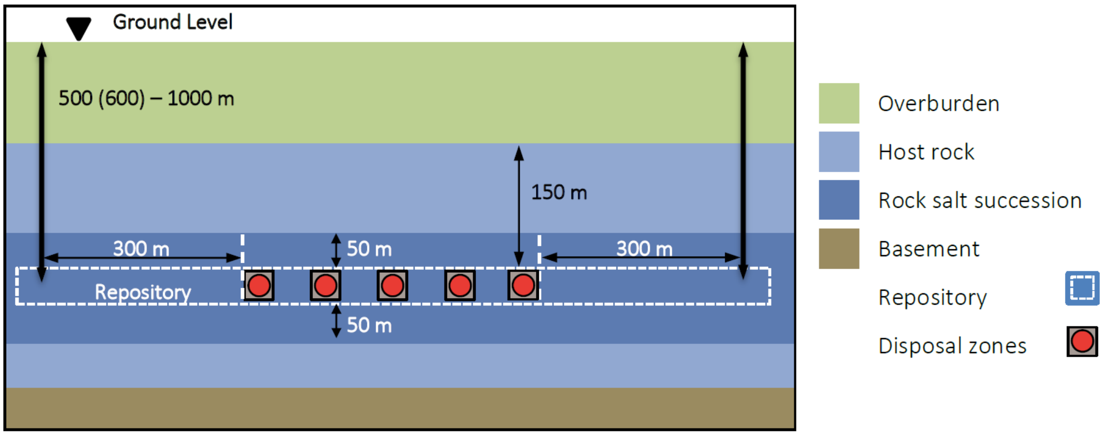


Figure 5-1: Safety distances of the sample repository in rock salt

2. As the covering evaporites have more than 150 m thickness in total, this criterion does not affect the suitability of the rock salt layer.

3. The minimum depth of 600 m below ground limits the position of the repository in the central and eastern part to a little extent, while the maximum depth of 1,000 m affects the western part.

The following figures 5-2 and 5-3 show the simplified geological formation. The safety boundaries separate the rock salt zone into unsuitable areas that do not fulfill the limits (blue) and the suitable ones (yellow). The dashed line marks the intersection of the two profiles. With a north-south as well as an east-west stretch of more than 8 km each and with a vertical range of more than 300 m the available space inside the rock salt is potentially able to host a repository with a variety of sizes, shapes and in several depths. This 3D-body is therefore the considered geology for a repository design

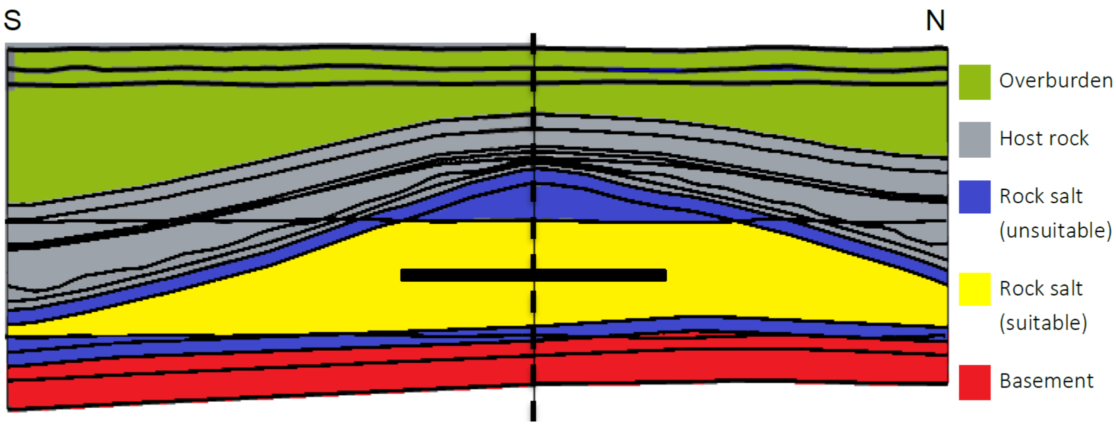


Figure 5-2: South-north cross-section near profile C-C' with simplified geology, restricted by safety distances for a repository (3x superelevated)

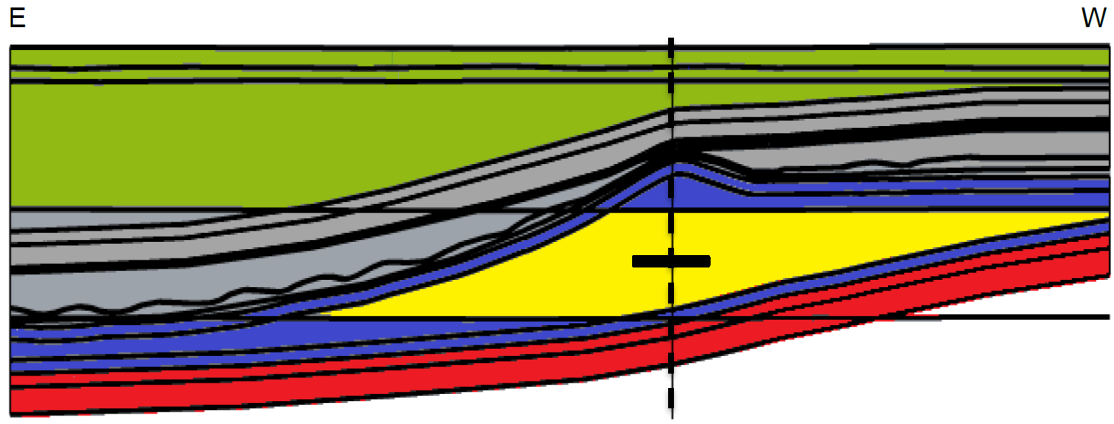


Figure 5-3: East-west cross-section near profile A-A' with simplified geology, restricted by safety distances for a repository (3x superelevated)

5.2.2 Repository design

HLW/SNF-repositories require long term safety without jeopardizing working safety. The design of the underground workings balances geological conditions, technical feasibility and regulatory requirements. In order to approximate an optimum, multiple design cycles are run.

The repository design is driven by the available space within the geological setting and the defined nuclear inventory. The stepwise approach first determines the geometry of individual excavations and organizes them into patterns that are specifically tailored to the geological conditions. Initially, one or more repository concepts are developed, and casks are selected accordingly for the various types of nuclear waste. Following this, the technical tasks are outlined, beginning with the handling of individual casks—how they will be transported, emplaced, or retrieved—and extending to considerations of necessary equipment and ventilation systems. These tasks ultimately define the geometry of the drifts.

To ensure the stability of drift contours and the pillars between them, geomechanical design is essential. Simultaneously, thermal design optimizes the spacing between casks, and, if needed, increases the distance between drifts to manage heat output. By allowing sufficient space around critical areas, the repository design not only enhances passive safety but also facilitates the installation of the engineered barrier system (EBS). The entire process is illustrated in the following figure 5-4.

The design is then used to plan geotechnical barriers, to verify their integrity considering different scenarios based on FEP analysis and finally to simulate radionuclide migration. If these assessments are successful, the layout can be considered as the final one.

The repository concept considers the disposal of self-shielded casks in horizontal emplacement drifts (ED) in one level only. These ED that are later backfilled with crushed rock salt are allowed to reach a maximum temperature of 200 °C. To take advantage of the salt pillow's thickness the repository is vertically centered in the suitable rock salt zone at a depth of approximately 750 m bgl. The sublevel structure is composed of the northern and southern emplacement wing and a central infrastructure area that hosts two vertical shafts. Each wing represents an emplacement area with multiple emplacement fields each containing a number

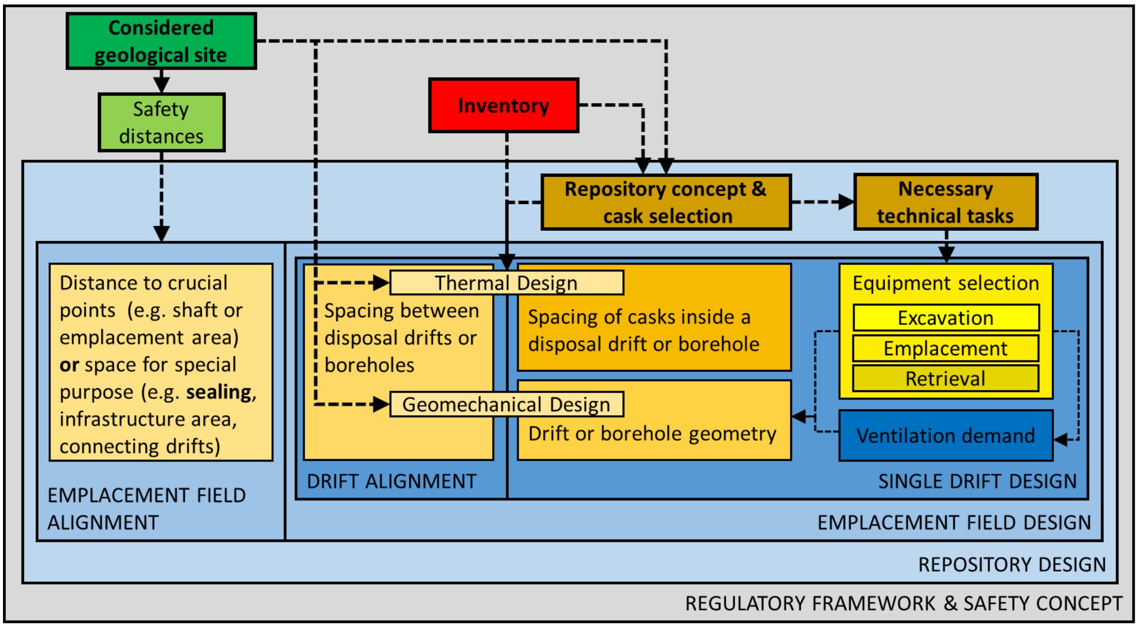


Figure 5-4: Concept of the repository design within the legal framework

of ED. The straight drifts and cross-cuts intersect at a 90° angle. Additional radii are planned for the transportation of casks via train.

Two shafts serve as dedicated fresh air intake and exhaust pathways, ensuring adequate ventilation while minimizing the disruption of the natural barriers. This design approach maintains the integrity of the geological layers, balancing ventilation needs with the preservation of the repository's natural isolation properties.

The infrastructure area and the ED are separated by at least 300 m of undisturbed rock salt. In order to minimize the quantity of access drifts only one drift leaves the infrastructure area to the west and one to the east. These split after about 100 m towards north and south. Each of these straight access drifts to the emplacement wings reserves a length of 500 m for the construction of drift seals in addition to the first 100 m. To ease the installation of the EBS these access drifts are inclined according to the allowed parameters of the transportation system. The shafts are located at the thickest part of the salt pillow to ensure that the longest natural barrier of rock salt can be used for sealing. Finally a lateral safety pillar of 500 m is applied (Figure 5-5).

The HLW/SNF inventory of Germany consists of different types and quantities of waste. There are SNF from pressurized water reactors (PWR), boiling water reactors (BWR) as well as from pressurized water reactors of the Russian type (VVER). Additionally there are three types of waste from reprocessing (CSD), structural parts from dismantling the SNF cells as well as SNF from prototype and test reactors. According to the safety and repository concept these need to be separately packed into different types of self-shielded casks.

Table 5-1 summarizes the radioactive waste inventory in Germany. The heat generating waste from SNF will be packed in a total of 2,120 POLLUX-10 casks. During packing the structural parts will be separated and loaded into 2,620 MOSAIK casks of type II. The different types of waste CSD-V, -B and -C coming from reprocessing will be loaded into a total of 887 POLLUX-

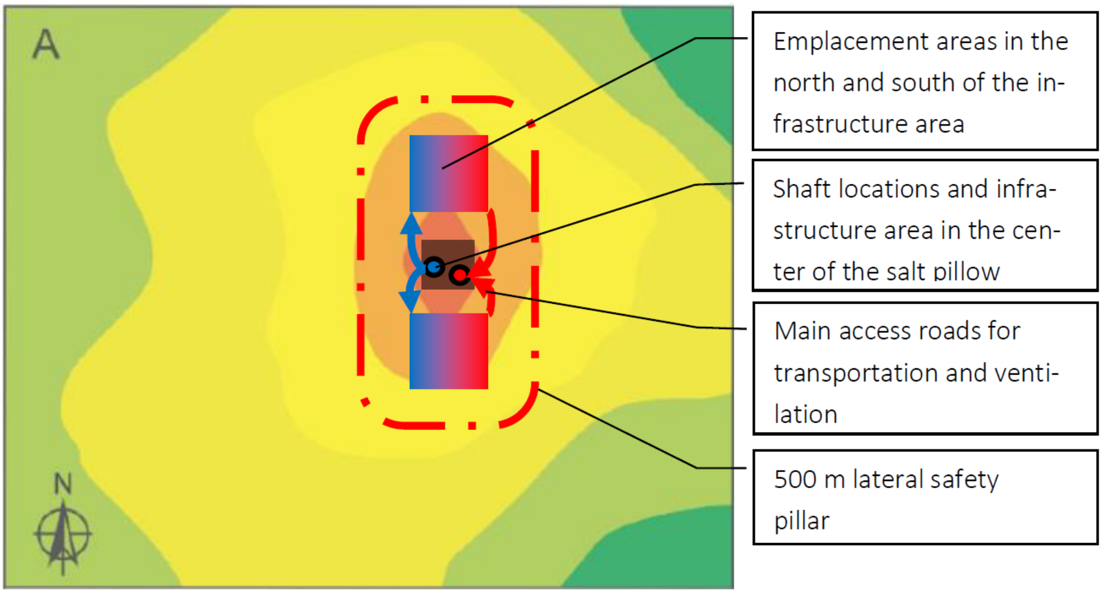


Figure 5-5: Elements of the repository concept within the selected geological site

9 casks. Spent nuclear fuel from prototype and nuclear test reactors will be disposed of in different types of CASTOR casks which are specially made for each type of waste. These sum up to a total of 530 casks (Bollingerfehr et al., 2018). The selected casks provide enough shielding to handle them without additional transportation cover.

Table 5-1: Summarized German nuclear inventory after Bollingerfehr et al. (2018)

Type of Waste	Quantity	Type of cask	Quantity
SNF	10,445 ton heavy metal	POLLUX®-10	2120
CSD-V	3,729 coquilles	POLLUX®-9	415
CSD-B & C	4,244 coquilles	POLLUX®-9	472
Structural Parts	Depending on SNF	MOSAIK® (Type II)	2620
SNF from prototype and nuclear test reactors	905,767 ball fuel elements + 2,536 fuel elements	CASTOR® THTR/AVR/KNK	461
	1,359 fuel elements + 16 fuel rods	CASTOR® MTR2	69

5.2.3 Thermal-mechanical design of the repository

This section describes the optimization of the repository by means of thermal-mechanical computations. The objective is to optimize the spacing between the casks in disposal drifts and between the drifts within the salt formation by maintaining a design temperature of no more than 200 °C at the cask surface.

Repository layout: The thermal design and optimization of space requirements are based on a schematic concept of the underground layout of the repository. This concept influences the thermal design and the calculation method for determining space requirements. The repository layout was previously described. It consists of an infrastructure area, where two shafts provide access to the surface, connects to the disposal area through two main drifts. These main drifts run parallel to each other and are interconnected at regular intervals by crosscuts. From these crosscuts, the disposal drifts branch off, which are parallel to each other and to the main drifts. The disposal drifts are blind, meaning they only have one access point from the crosscut. In the disposal drifts, the waste containers are placed on the floor.

Waste packages: The drift disposal concept for salt formations draws significantly from the comprehensive insights obtained from the preliminary safety analysis at the Gorleben site, as detailed by (Bollingerfehr et al., 2013). This analysis not only explored the feasibility of waste emplacement in drifts but also contributed to the foundational knowledge in this domain. Furthermore, the advancement in emplacement technology for the final disposal of POLLUX® casks, as documented by (Engelmann et al., 1995), continues to stand as contribution to the state of the art in drift disposal methodologies and techniques.

In this concept, spent fuels and reprocessed waste are package in POLLUX® casks. The remaining waste type such as waste from prototype, research and experimental reactors are packaged in various CASTOR® casks. For the thermal design, only the heat generating waste in POLLUX® casks are considered. Minimal spacings based on mining and pillow stability requirements are considered for the disposal of the CASTOR® casks.

Figure 5-6 illustrates the temporal evolution of the thermal output of different types of fuel elements in a loading configuration equivalent to that of PWR fuel elements. The mixed loading, comprising 89% UO2 and 11% MOX, conservatively covers the heat release from the UO_2 fuel elements used in BWR (Boiling Water Reactor) and VVER (Water-Water Energetic Reactor) reactors. The thermal output for pure MOX fuel element loadings is compared in the figure.

Additionally, Figure 5-6 presents the thermal power of reprocessed waste. It exhibits a decay behavior distinct from that of the fuel elements. The heat output of such wastes remains at the level of the UO_2 fuel elements initially, then declines more significantly after 50 years post-reprocessing.

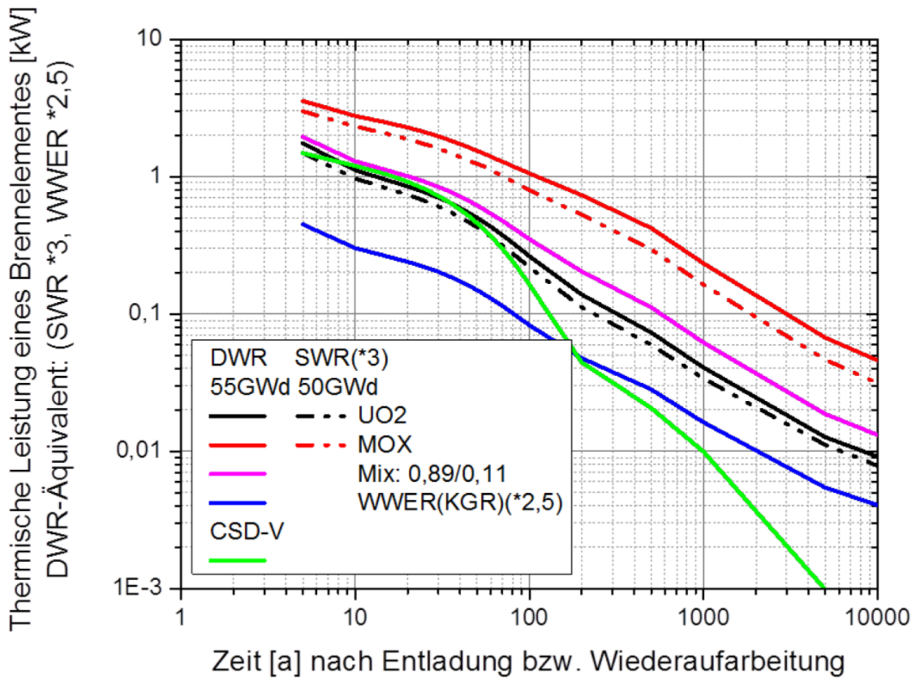


Figure 5-6: Heat power of different heat generating radioactive waste

The POLLUX® cask was specifically designed and engineered for final disposal in salt formations. For this study, it is assumed that POLLUX® casks can accurately approximate future final disposal containers for drift disposal in rock salt in all relevant characteristics, ensuring that using this type of container does not introduce a significant error in determining the space requirements for disposal variants.

The POLLUX® container consists of an inner and an outer container, see Figure 5-7. The inner container is made of fine-grain structural steel (material 1.6210) and is hermetically sealed with a screwed primary lid and a welded secondary lid. The interior is divided into several chambers, each of which can accommodate a fuel rod assembly with fuel rods from two PWR assemblies or six BWR assemblies. By adjusting the interior, the storage of CSD molds is conceptually possible. Figure 5-7 illustratively shows a POLLUX® container with withdrawn fuel rods from ten PWR assemblies (POLLUX®-10). The external shielding container, like the primary and secondary lids, is made of ductile cast iron (material 0.7040). This shielding container is not required to be leak-tight and is closed with a screwed lid. In the shell, rods of polyethylene are inserted in radially distributed bores to reduce neutron dose rates. The structural design and material selection of the container ensure the fundamental requirements for retrievability during the operational phase. Regarding the requirement of handle-ability of the container up to 500 years (retrievability), no corresponding studies have been conducted yet. The container underlying this analysis has a length of 5.517 meters and a diameter of 1.56 meters (Bollingerfehr et al., 2013).

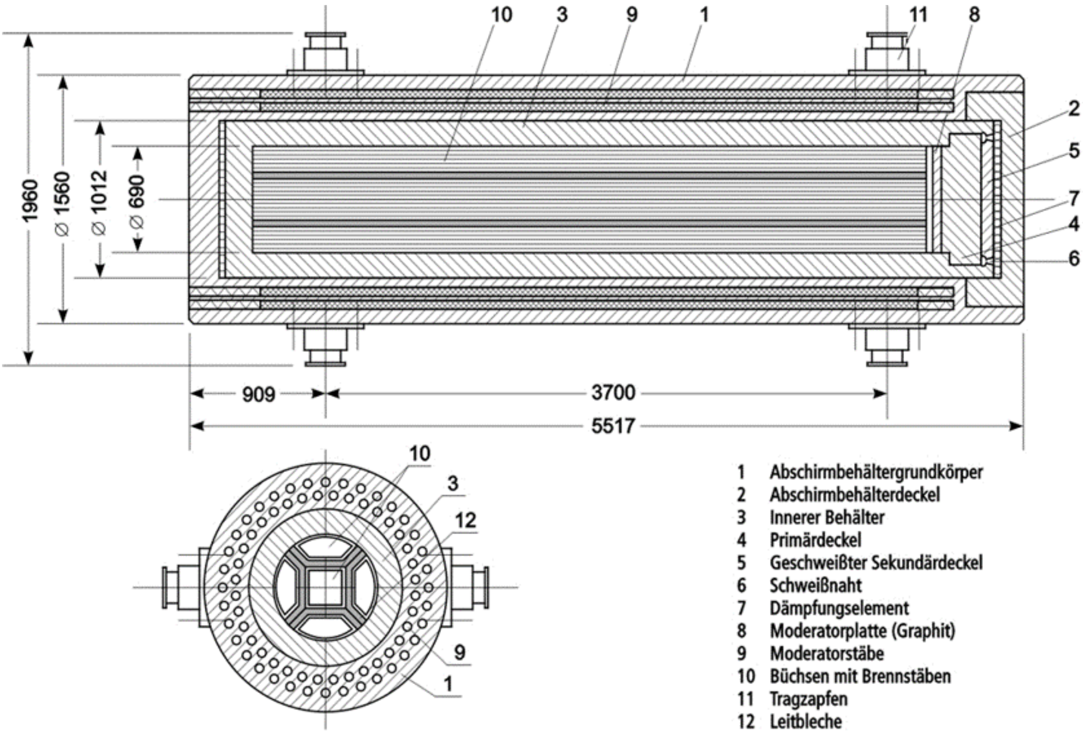


Figure 5-7: Schematic illustration of a POLLUX® cask (Bollingerfehr et al., 2013)

Numerical modelling: The design temperature for disposal in rock salt was set at 200 °C on the outer surface of the final disposal container, aligning with the limit temperature established in previous projects Bollingerfehr et al. (2013, 2018). Thermal design calculations are conducted for this temperature, varying the casks and drift spacings within a parameterized calculation model. This model, representing the repository, needs to illustrate thermal superpositions and the resulting temperature increases. Such representation can be achieved by considering thermal symmetry boundary conditions as a quarter model of a cask embedded in a partial model of the rock formation, allowing the simulation of a horizontally extensive disposal field with a grid based on cask and drift distances. In this model, the distance from the drift axis to the model boundary in the transverse direction of the drift equals half the drift distance, and the distance from the cask's end face to the model boundary in the drift direction equals half the cask distance. The resulting thermal superpositions are conservative and only occur in storage fields with very long storage drifts and a large number of such drifts. This modeling approach has the advantage of not requiring the entire repository to be modeled, reducing time and numerical effort. The calculation model is depicted in Figure 5-8, showing a drift filled with crushed salt in a salt formation where a final disposal cask is stored. The cask in the model comprises two components: an outer casing for shielding against radioactive radiation and a container basket holding the high-level radioactive wastes, acting as a heat source in the model.

For this analysis, models were created for disposal depth of 810 m below the ground level.

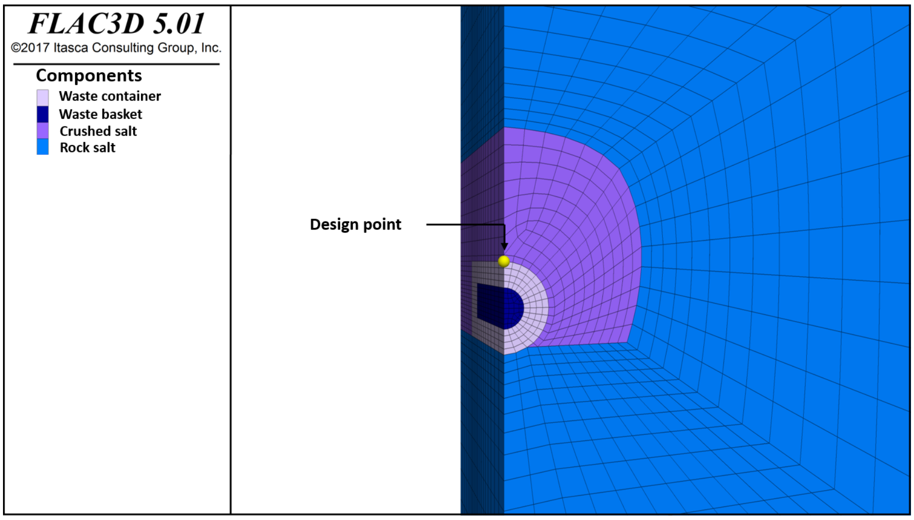


Figure 5-8: Numerical model for the thermal-mechanical design of disposal drifts with heat generating waste

Table 5-2 summarizes the material areas used in the model to simulate thermal propagation in the near field - rock salt. The crushed salt considered in the calculation model is compacted over time under the influence of lithostatic stresses, changing its thermal properties, particularly its thermal conductivity. The mechanical material model of the crushed salt capturing this compaction behavior and its material parameters are detailed in Bollingerfehr et al. (2013). The compaction of the crushed salt, dictated by the material properties of the rock salt, exhibits a viscosity-dependent deformation behavior influenced by stress and temperature, hence time-dependent. The material model used for rock salt is also described in Bollingerfehr et al. (2013).

Table 5-2: Density and thermal parameters of the components in the near field of the disposal drift (η: porosity, T: temperature)

Components	**Density [kg/m³]**	**Heat Capacity [J/kg K]**	**Thermal Conductivity [W/m K]**
Container	7000	515	15
Container basket	7000	500	20
Crushed salt	f(η) : 1430 – 2200	f(η) : 562 – 864	f(η) : 5.4 – 0.7
Rock salt	2200	864	f(T) : 5.4 – 4.2

The computations was carried out thermal-mechanically with FLAC3D in the version 5 (Itasca Consulting Group, Inc., 2021).

Modeling results: The thermal design is conducted by varying the spacing between the drifts. The spacing between the casks was set to a constant value of 3 meters allowing to dispose the maximum amount of casks in a single drift. The drift spacing was varied in increments of five meters. For the design, the loading of the casks with ten fuel elements was considered based on the experience gained from previous projects. The temperature evolution curves for different spacing at the design point are depicted in Figure 5-9

The temperature evolution at the design point of a cask in the central area of a disposal field, loaded with PWR mixed fuel elements based on their thermal output, is characterized by up to three peaks. The first peak is reached immediately after storage and is due to the thermal-mechanical behavior of crushed salt. Right after emplacement, the crushed salt acts as an insulator due to its initially low thermal conductivity, leading to the formation of the first temperature peak. This peak is influenced by the load and the distance between the casks. Subsequently, as the thermal conductivity of crushed salt increases due to compaction, the temperature drops. Whether a second peak, a plateau, or a mildly increasing or decreasing region forms around 50 years depends on the geometric configuration. Another temperature peak forms after about 400 years due to thermal superposition effects. Depending on the geometric setup, different peaks may be significant for the design. The temperature progression in a disposal field where VVER fuel elements are emplaced shows similar behavior as the PWR fields. The thermal outputs of PWR mixed and VVER fuel elements have approximately the same rate of change.

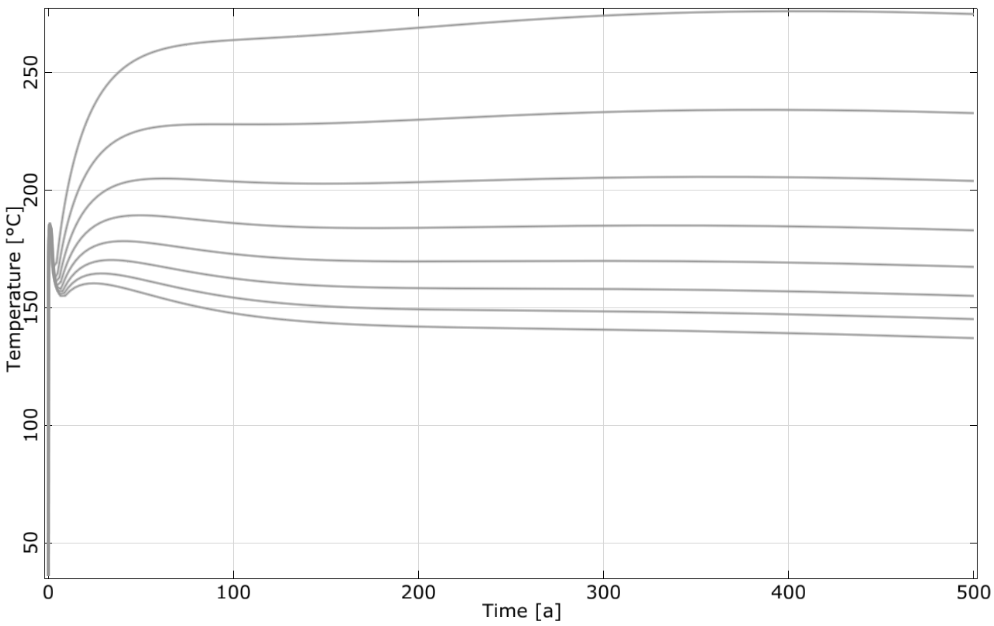


Figure 5-9: Temperature evolution at the design point of a POLLUX® cask with PWR spent fuels

The temperature peaks from Figure 5-9 were plotted in Figure 5-10 as a function of the drift spacing, identifiable by the support points. In Figure 5-10, it results that a spacing of about 37.5 m and higher is necessary to meet the temperature limit of 200℃ at the cask surface. Thus the spacing of 37.5 m is assumed for the planning of disposal fields emplaced with PWR spent fuels. The same spacing is conservatively assumed for VVER emplacement fields as the thermal output of this waste type is similar to that of PWR but with a lower amplitude.

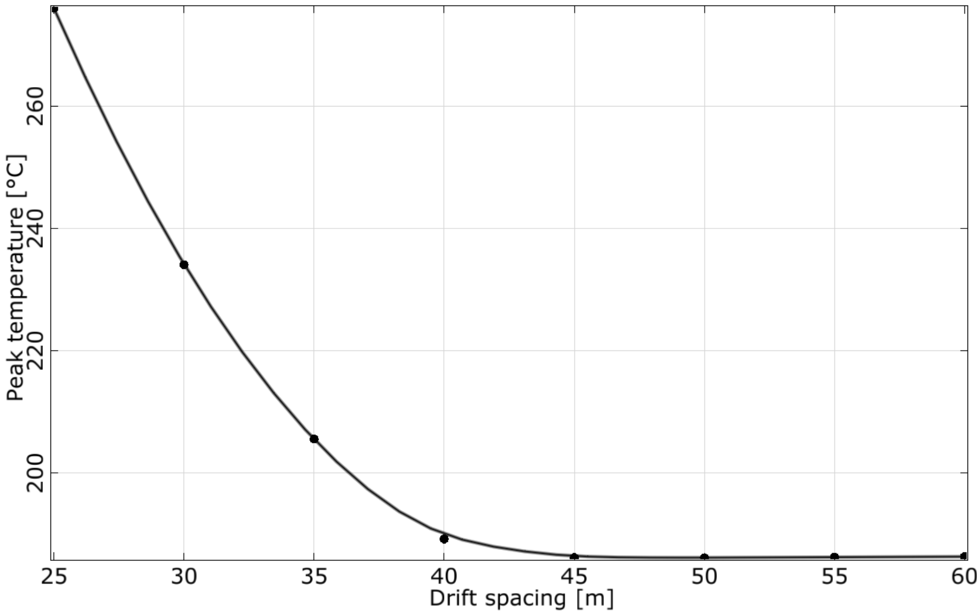


Figure 5-10: Temperature peak as a function of the drift spacing for POLLUX® cask with PWR spent fuels

The thermal design for the CSD-V emplacement field is carried out analogously to the spent fuel with a cask spacing of 3 meters and a cask loaded with a maximum of 9 CSD-V canisters.The temperature evolution curves for different spacings at the design point are depicted in Figure 5-11. The design calculations for disposal areas with CSD-V are performed similarly to those for areas with fuel elements. The characteristic temperature progression for CSD-V, marked by two temperature peaks, is due to a more significant drop in its thermal power curve, as shown in Figure 6 3. A first temperature peak forms immediately after storage due to the previously mentioned thermal-mechanical behavior of crushed salt. The second temperature peak is reached around 40 years after storage. Depending on the container load and geometric configuration, either the first or the second temperature peak may be critical. Instead of a second peak, a slightly declining temperature plateau may also form.

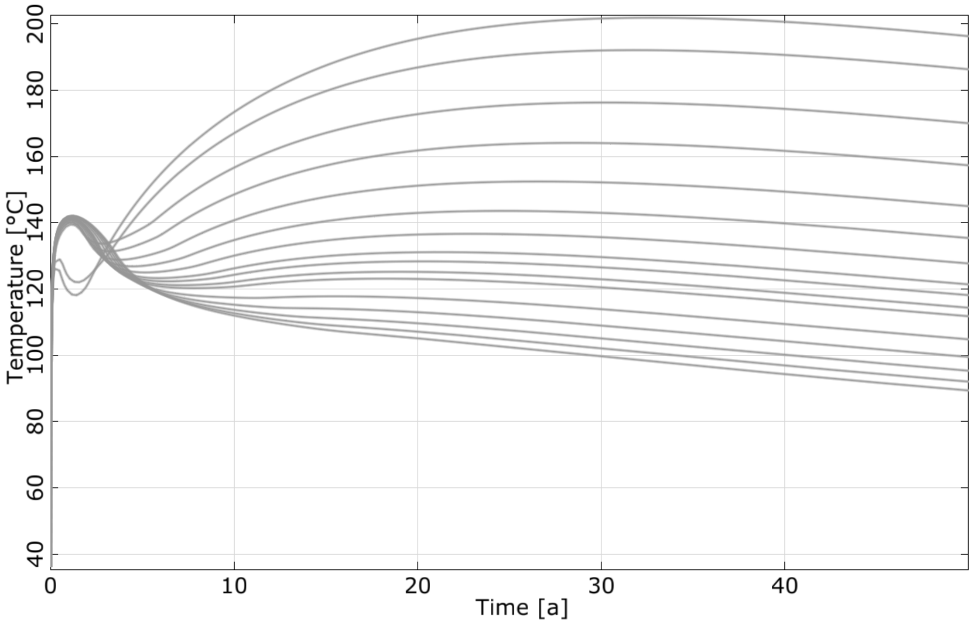


Figure 5-11: Temperature evolution at the design point of a POLLUX® cask with CSD-V waste

The thermal design for the CSD-V emplacement field is carried out analogously to the spent fuel with a cask spacing of 3 meters and a cask loaded with a maximum of 9 CSD-V canisters. Thus, only the drift spacing was optimized. The temperature peaks from Figure 5-11 were plotted in Figure 5-12 as a function of the drift spacing, identifiable by the support points. In Figure 5-12, it results that a spacing of about 15 m and higher is necessary to meet the temperature limit of 200℃ at the cask surface. Thus the spacing of 15 m is assumed for the planning of disposal fields emplaced with CSD-V reprocessed waste.

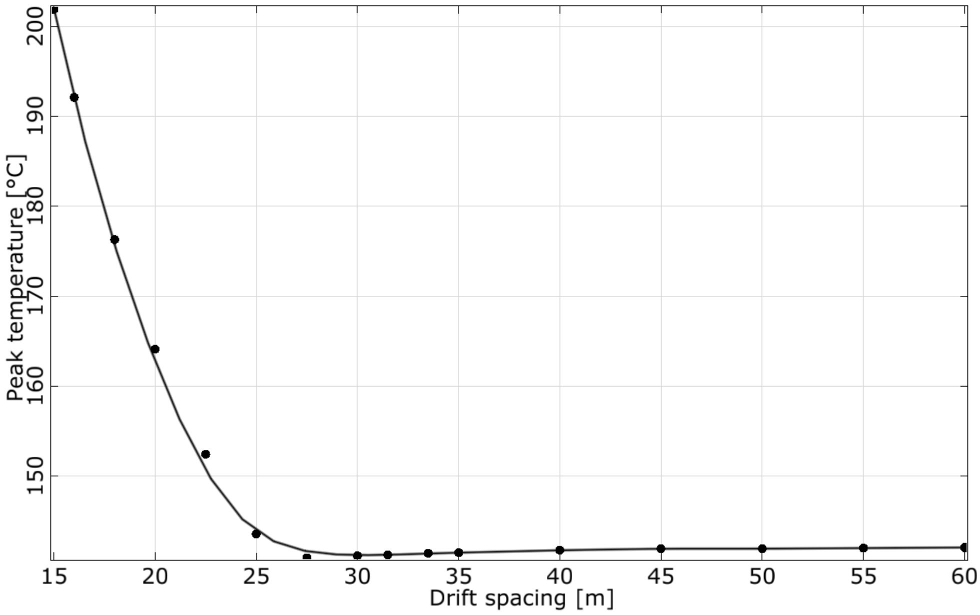


Figure 5-12: Temperature peak as a function of the drift spacing for POLLUX® cask with CSD-V waste

5.2.4 Layout of the repository

The rectangular drift system consists of the following types of drifts that are arranged in one level only:

- Infrastructure cross cut (east-west orientation) from the infrastructure area towards the main drifts
- Main drift for waste transport (north-south orientation)
- Main drift for excavation transport (north-south orientation)
- Cross cuts between the main drifts inside an emplacement wing (east-west orientation)
- Emplacement drifts (ED) (north-south orientation)

As the sizes of the drifts are taken from the project KOSINA (Bollingerfehr et al., 2018) (see Figure 5-13) only the spacing of casks is required on the scale of single drifts. While each cask creates an envelope of heat around itself due to the contained material, two or more overlapping envelopes can lead to an even higher temperature. The thermal-mechanical design varies the pattern of the casks within a drift and between drifts to calculate the temperature in the surrounding area over time. These cases are then combined to a function between the two spacing directions and the corresponding temperature. From all combinations that remain below 200 ℃ a one is used, were a single ED can accommodate relative many casks, while the spacing between ED is comparatively large. These conditions minimize the quantity of drifts and preserve strong pillars. Under the given conditions POLLUX®-10 casks with SNF will have a spacing of 3 m from shoulder to shoulder and 37.5 m between the axis of a cask and the axis of a cask in the adjacent drift. POLLUX®-9 casks with CSD-V only require a minimum spacing of 3 m by 15 m. All other POLLUX®-9 and CASTOR casks are spaced 1 m for technical reasons while the distance between their ED is negligible.

Additionally a geomechanical design is required to secure the stability of the pillar. According to a rule of thumb a rock salt pillar should be at least twice as wide as the adjacent drifts. Here it is defined that it needs to be twice the width of the wider adjacent drift. Because it needs to maintain its stability also in case of retrieval, the largest size of the current and potential drift has to be used. The size of the main drifts does not change during retrieval, as there are no obstacles or a heat concentration. The ED for structural parts can be reopened without changes, too. According to the concept of the ERNESTA project (Herold et al., 2018) the ED for POLLUX are reopened by drifting smaller profiles on both sides along the original drift in the first place. Then the remaining salt between the two is removed in a second step. The full profile for retrieval therefore has a width of 9.7 m. This concept is altered for the retrieval of CASTOR casks. In this case a single adjacent drift will be used to prepare reopening the ED. For the given inventory the following distances are defined. The selected spacing between drifts is now equal to the largest required distance. Table 5-3 and Figure 5-13 summarizes the proper-ties of the drifts.

Table 5-3: Width of drifts and required rock salt pillars in meters

	Main Drift Control Area	**Main Drift Moni-toring Area**	**ED Pollux-10 SNF**	**ED Pollux-9 CSD-V**	**ED CAS-TOR**	**ED MO-SAIK Structural Parts**
Drift width required for emplacement	7.60	6.80	5.10	5.10	5.10	5.50
Drift width required for retrieval	7.60	6.80	9.70	9.70	7.10	5.50
Optimized spacing from thermal design (axis - axis) [wall – wall]	0.00	0.00	37.50 [32.40]	15.00 [9.90]	0.00	0.00
Geomechanical rock pillar width (wall - wall)	15.20	13.60	19.40	19.40	14.20	11.00

If different types of drifts are adjacent to each other the larger required distance is used. An exception is made between ED for SNF and cold drifts e.g. the ED for structural parts or the main drifts as these will not increase the maximum temperature.

The ED are planned with a length of 250 m of which 225 m can be used for disposal. Based on the spacing of casks and their length the maximum quantity per ED can be calculated. The total quantity of a cask type divided by the quantity per ED equals to the number of ED needed. The distance between main drifts is 800 m. The crosscuts that develop the em-placement fields are planned with a maximum length of about 790 m. Based on the spacing between drifts the number of drifts per cross cut is calculated. The number of ED divided by ED per crosscut finally gives the quantity of emplacement fields needed. In this case a total of 5.8 emplacement fields is needed, see Table 5-4.

The arrangement of the drifts uses following principles:

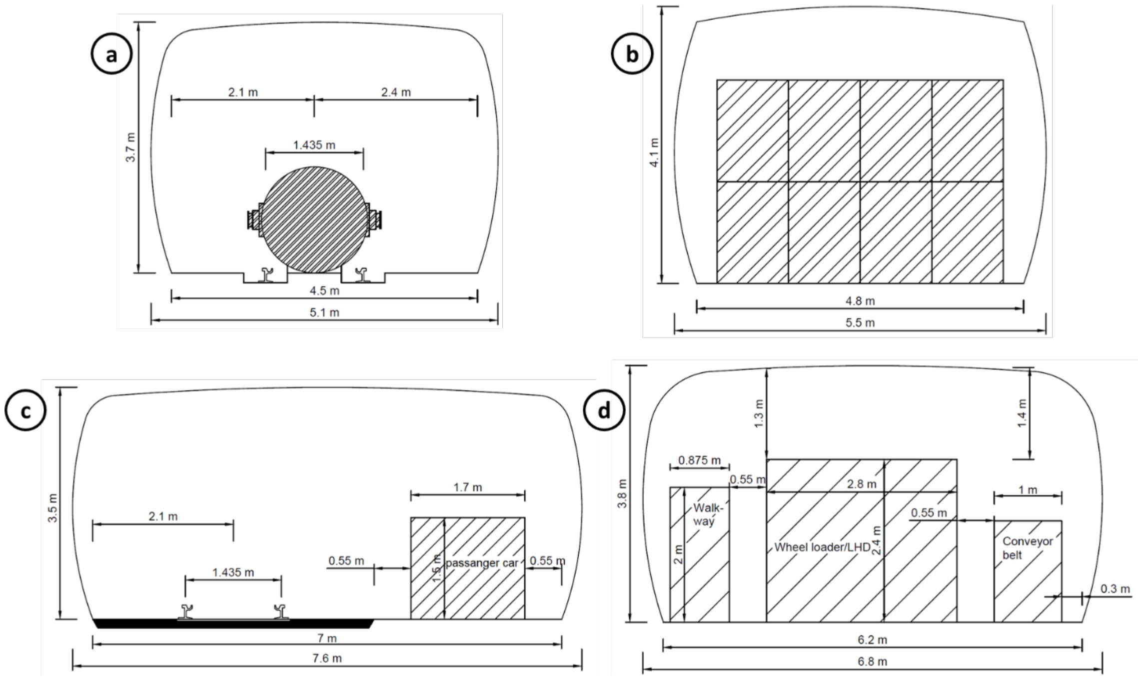


Figure 5-13: Illustration of the drift profiles for POLLUX emplacement drift (a), MOSAIK emplacemnet drift (b), main drift for waste package transport (c) and main drift for mining operations (d)

Table 5-4: Number of emplacement fields required for different types of waste

	POLLUX®-10	**POLLUX®-9**	**CASTOR® var. types**	**MOSAIK type II**
Cask quantity [m]	2,120	887	530	2,620
Cask length [m]	5.60	5.60	2.90	1/7
Cask spacing [m]	3	3	1	0
Number of casks per 225 m usable ED	26	26	57	1,800
Number of ED needed	82	35	10	2
Drift spacing (axis - axis) [m]	37.5	29.1	21.3	16.5
Number of drifts per 790 m crosscut	20	26	36	46
Number of fields required	4.1	1.3	0.3	0.04

- One ED can only be used for one type for waste
- If one type of waste requires a multiple ED these should be grouped together
- “Hot” waste is disposed in fields near to the infrastructure area to foster salt creep and therefore the self-sealing of drifts that have been backfilled with crushed salt
- The emplacement process starts at the far end of one wing close to the main drift of the monitoring area. It continues in a retreating operation towards the main drift control area.
- At first the already packed and comparatively “cold” waste types in CASTORS are disposed of, POLLUX-9 and POLLUX-10 follow in the next steps

- Waste out of structural parts is commissioned during the packing of SNF. Therefore in both fields an ED is required. As it needs to be open until the last bit of structural waste is taken from SNF it should be closer to the infrastructure area
- One ED can only be used for one type for waste
- If one type of waste requires a multiple ED these should be grouped together
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- The emplacement process starts at the far end of one wing close to the main drift of the monitoring area. It continues in a retreating operation towards the main drift control area.
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- Waste out of structural parts is commissioned during the packing of SNF.

Therefore in both fields an ED is required.

As it needs to be open until the last bit of structural waste is taken from SNF it should be closer to the infrastructure area

Figure 5-14 shows the layout of the developed repository. A symmetrical arrangement of three emplacement fields in each wing offers enough space for the anticipated waste. Although not all 6 are fully required the northern wing is the first to go into operation. Here all SNF from test and prototype reactors as well as waste from reprocessing and a minor number of the SNF waste including its structural parts will be disposed here. Time-displaced the southern wing will be developed and will commence operation. Here the remaining part of the SNF will be emplaced with the corresponding structural parts. If a need for a few additional ED arises during the operation of the northern wing, which will be used to 100%, the southern wing has a reserve to cope with that demand. The ready repository design can be seen in following figure. With a total length of less than three kilometers and about 800 m width it fits well into the suitable space of the salt pillow.

The emplacement fields are separated from the infrastructure area by at least 300 m of undisturbed rock salt. The two shafts do not influence each other as their safety pillars are far apart. The straight drifts allow the installation of belt conveyors and good vision while driving. It is thought that the waste is transported with an electrical locomotive that drives forward in the main drifts, then turns into a cross cut. Here it passes the switch of the current ED, stops and reverses into the ED. A maximum decline between 2.5 % and 4.0 % is assumed to be suitable for the locomotive on straight sections. Therefore an inclination of 4.0 % will be used in the access drifts between the infrastructure cross cut and the emplacement wings to support the construction of the seals, see Figure 5-14.

Figure 5-15 shows a stylistic 3D representation of the repository system where the developed repository mine is integrated into the generic geological formation. Here we can see that the shafts are located where the salt pillow thickness is maximum.

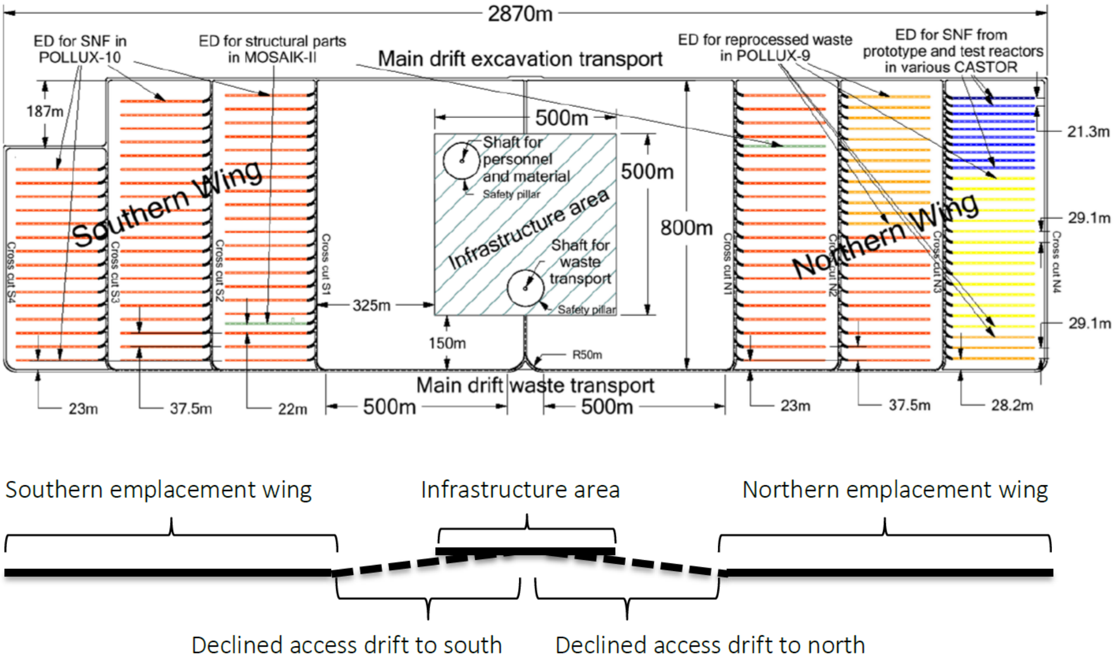

Figure 5-14: Repository design in topview and frontview

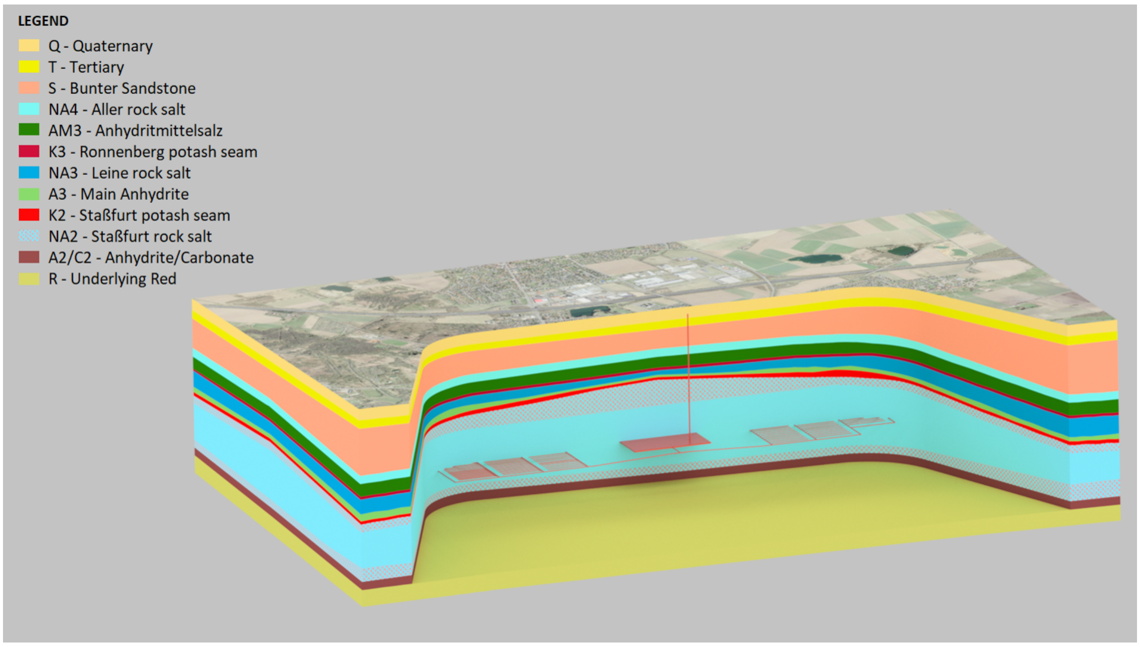

Figure 5-15: Generic repository system for RANGERS (with courtesy of BGR (Völkner et al., 2017a))

6 Sealing Concept

The sealing concept includes the conceptual design of the geotechnical barriers or the EBS and describes the functions and functional periods of those barriers.

6.1 Regulatory requirements

In general, when designing a deep geological repository, it is essential to ensure that the deposited radioactive waste remains reliably isolated from the biosphere over a long period of time. This is also the key statement of Section 4 of the EndlSiAnfV (EndlSiAnfV, 2020). It states:

> *(1) The radioactive waste to be deposited in the repository system must be concentrated and securely enclosed with the aim of keeping the contained radionuclides away from the biosphere for at least the assessment period.*
>
> *(2) The intended repository system must ensure the safe confinement of the radioactive waste passively and maintenance-free through a robust, layered system of various barriers with different safety functions.*

The use of the term repository system indicates that the secure confinement must be achieved through the interaction of the geological barrier (the rock of the repository site) with the technical and geotechnical barriers. Even the most suitable location can only serve as a safe repository with the repository rock if it is possible to adequately seal the necessary penetrations of the repository rock after the completion of the waste emplacement (Wunderlich et al., 2022).

The EndlSiAnfV (EndlSiAnfV, 2020) specifically requires the inclusion of a sealing concept in the development of the safety concept (Section 5, §10). Furthermore, measures to concretize the sealing concept are to be specified in the repository concept (Section 5, §11). In Section 2, §19, the EndlSiAnfV further detailed which components of the repository system has to be sealed and closed by stating that the sealing and closure of the repository includes, in particular, the as complete as possible backfilling of all underground cavities and their sealing, as well as the dismantling of technical facilities that impair long-term safety.

In the United States, the shaft sealing system developed for the Waste Isolation Pilot Plant (WIPP) and reviewed and certified by the Environmental Protection Agency (EPA) can serve as a foundation for the development of a sealing concept for a salt repository safety case. If a Department of Energy (DOE) repository for High-Level Waste (HLW) and Spent Nuclear Fuel (SNF) were to be located in the Delaware Basin bedded salt, any modifications made to the WIPP seal design would enhance its primary functions. These functions include limiting the migration of waste constituents to regulatory boundaries, restricting the flow of formation water through the seal system, preventing structural failure of system components, and mitigating subsidence and accidental entry. As a result, the DOE can have a high level of confidence that the sealing system for a repository containing DOE HLW/SNF will meet the requirements associated with the performance of the repository system (MacKinnon et al., 2012).

6.2 Reference to the safety concept

According to the EndlSiAnfV, the safety concept must provide an overview of all planned barriers within the repository system, particularly the essential barriers, their respective safety functions, and how they interact. The essential barriers are defined as the barriers on which the secure containment of radioactive waste primarily relies. In addition to the essential barriers, the safety concept also defines additional barriers that work together with the essential barriers to prevent or limit the release of radionuclides.Thus, the sealing elements are to be divided into essential barriers and additional barriers. To differentiate the functions of each barrier conceptually, safety functions are assigned to the essential barriers, while protective functions are assigned to the additional barriers.

In this context, the safety function is defined as a property of a component within the repository system that fulfills safety-related requirements for the secure containment of radionuclides. To enable these safety or protective functions to be performed by each component, specific performance targets must be assigned during the conception of the individual modules of each component. Performance targets are measurable or calculable quantities or characteristics by which the fulfillment of the associated safety function can be quantitatively assessed. To achieve these performance targets, it is necessary to formulate specific design requirements for the construction of the structures or their individual modules. These requirements must be adhered to in order to definitively achieve the desired performance targets of the structure. From the design requirements, design specifications are derived, which serve as the basis for the manufacturing and construction of the structure or its individual parts. Compliance with the design requirements must be verified during the construction of the structure, taking into account quality assurance measures.

Design premises of the sealing concept can be derived from the safety concept (see section 4.2) and the regulatory frame (see section 4.1). The Ordinance on Safety Requirements for the Disposal of High-Level Radioactive Waste (EndlSiAnfV 2020) states that

> *[...] the integrity of the system of essential technical and geotechnical barriers shall be demonstrated for the expected developments during the verification period and its robustness shall be justified. It shall be demonstrated that the properties of the further barriers of the repository system relevant for the safe confinement of the radioactive waste and, in particular, of the rock mass in the emplacement area are maintained at least over the period of time during which they are required according to the safety concept.*

Further it is required to demonstrate the integrity of the essential technical and geotechnical barriers. This assessment shall demonstrate the safety functions of the barriers and their resistance against chemical and physical processes resulting in corrosion or erosion, the stress state or changes in the stress state and the temperature development over time. Following this the sealing concept must be:

1. designed in a diverse redundancy
2. composed of a modular system to react on variations in the geological environment shaft and drift seals

3. separated in different modules/elements with sealing function and stability function
4. able to cover different functional periods of the modules/elements and guarantee the function over the required period

Diverse redundancy means that different components with possibly different functional principles work together. With this type of redundancy, the risk of systematic error is minimized.

Waste form and disposal waste package represent components of the EBS as well. In the considered safety concept for salt, based on the German regulatory frame, both technical components of the EBS have no explicit long-term sealing function. They provide at first operational safety function. Within the sealing concept the geotechnical barriers of shaft and drift sealing as well as the backfill are considered. The following design includes the shaft and drift sealing. The backfill inside all emplacement drifts, cross cuts and main drifts is made of crushed rock salt.

Shaft seal and drift seal are connected to specific safety functions as the sum of properties to fulfill the required safe containment of the radionuclides. This safety function can be broken down to further target properties, defining measurable or calculable characteristics of single modules/elements by which the fulfillment of the associated safety function can be quantitatively assessed. The target properties will be translated in design requirement by giving the measureable characteristics a value of a range to be fulfilled. The design requirement will defined within the design process of the EBS. The resulting preliminary design is afterwards evaluated in the EBS assessment and the PA.

As previously mentioned in the preceding section, specific measures need to be formulated to provide concrete details to develop a sealing concept outlined below. These measures are derived from the safety concept and serve as the basis for the development of the are incorporated into the repository concept. From research projects and safety assessment evaluation like the preliminary safety assessment for the Gorleben Site (Mönig et al., 2012), KOSINA (Bollingerfehr et al., 2018) and RESUS (Bertrams et al., 2020), several measures has been formulated in the safety concept concerning the sealing of a repository in salt. Although, these measures were derived from previous safety requirements (BMU, 2010), they are still valid for the requirements formulated in EndlSiAnfV (2020). Those measures are (Mönig et al., 2012):

- In the shafts and access tunnels connecting the infrastructure area to the emplacement areas, sealing structures with a specified hydraulic resistance are constructed and quality assured. These sealing structures must remain sufficiently tight until the hydraulic resistance of the compacted salt crushed salt is sufficiently high to prevent or limit the inflow of solutions to the waste. Therefore, their effectiveness must be ensured for at least the duration required for adequate backfill compaction. The design of the sealing structures is based on load cases that cover a range of possible future developments during their required service life as much as possible.
- The open cavities in the mine workings of the emplacement areas are backfilled with crushed salt. The cavity convergence due to salt creep leads to compaction of the crushed salt, reducing its porosity and permeability. Near the heat-generating waste, crushed salt compaction is accelerated by locally elevated temperatures. The cavity convergence is limited by the volume of crushed salt. The earlier onset of confining

stress compared to unfilled mine workings and the overall reduced extent of salt creep lead to accelerated healing of the rock salt in the excavation disturbed zone and a reduction in differential stresses within the rock mass. Furthermore, the introduction of backfill significantly reduces the initial cavity volume that can be filled with solution.

- In the access drifts, a sufficient sealing effect of the backfill is aimed to be achieved within a short period. Therefore, the crushed salt in the access drifts belonging to the emplacement areas is slightly moistened to reduce its resistance to compaction and achieve faster compaction
- Moisture introduced near the waste in the repository is minimized. The aim of this measure is to limit corrosion of the waste containers and thus the generation of gas and gas pressure buildup within the repository. For heat-generating waste, where only small amounts of residual moisture may be present, crushed salt backfill with very low moisture content is used in the mine workings of the emplacement fields.
- The design of the shaft sealing structures is based on the use of multiple sealing elements made of different materials, each with diverse functional properties due to their respective construction

6.3 Components of the sealing concept

The sealing concept for a repository in salt involves geotechnical barriers and the backfilling of cavities, at least in the emplacement areas, with compacted crushed salt. The geotechnical barriers encompass shaft seals and selected drift seals. Together with the containment-providing rock zone, they ensure the confinement of the radioactive waste in the early phase of the repository evolution during the period when the crushed salt has not yet fully developed its sealing effect (Mönig et al., 2012).

The shaft seal is the most important safety-related closure, as it restores the integrity of the containment-effective rock mass. Its main function is to prevent water/solution ingress from the overlying rock into the repository after its closure and, in the event that radionuclides are mobilized during the post-closure phase, to retain them within the repository through appropriate sealing. The concept of a shaft seal includes sealing components as well as supporting/structural components (Kreienmeyer et al., 2008). The shaft seals are designed to withstand the expected fluid pressures (hydrostatic pressure from the water column in the overburden and surrounding rock). The design of the shaft seals assumes a functional lifespan of 50.000 years (up to next ice age) in Germany, during which their functionality must be ensured. After this time period of about 50.000 years, increased hydraulic permeability of the shaft seals and therefore enhanced solution ingress into the infrastructure area are assumed for the reference scenario. If solutions reach the drift seals, partial dissolution of the sealing materials or precipitation of dissolved inventory in the pore space can occur. At that time, the backfilled crushed salt in the access drifts already exhibits a low permeability similar to the intact rock (Beuth et al., 2012).

At defined locations separating the emplacement areas from the infrastructure area within the repository mine, drift seals are constructed. Their purpose is to prevent solutions from reaching the emplacement fields or to delay the spread of contaminated solutions until the compacted crushed salt can assume the barrier function of sealing repository system. For the reference scenario, a functional lifespan of 50.000 years is assumed for the tunnel seals, during which their functionality must be ensured. The required integral permeability is set at $5 \cdot 10^{-17} m^2$ (Beuth et al., 2012). The drift seals must be designed to withstand the rock pressure exerted by the surrounding rock. This pressure is determined by considering possible stress redistributions based on petrostatic considerations" (Kreienmeyer et al., 2008, p. 42). For drift seals, the separation of sealing and supporting components is recommended, as well as the design with redundant and diverse components and materials (Kreienmeyer et al., 2008).

In salt repository concepts developed in Germany (VSG (Mönig et al., 2012), KOSINA (Bollingerfehr et al., 2018)), the infrastructure area is to be backfilled with non-compactable gravel made of basalt or serpentinite. Unlike crushed salt, this non-compactable backfill undergoes only slight compaction due to the increasing convergence, quickly generating confining stress. The infrastructure area, filled with non-compactable backfill, serves as a reservoir for solutions entering through the shaft and from the host rock. It can also serve as a reservoir for gases generated within the repository due to corrosion of the disposal caks. In the preliminary safety case for the Gorleben site, the backfilled infrastructure area was planned to served as a reservoir to collect 5.100m^3 of fluid resulting form the inflow of solution through the shaft into the infrastructure area (Beuth et al., 2012).

Besides the geotechnical barriers, the waste packages and the waste form are also part of the EBS and the sealing concept.

6.4 EBS design guidance

The design of the EBS will be prepared in a stepwise approach with the possibility of additional iterations, if safety function or requirements cannot be fulfilled by the preliminary design. The approach considers the previously named R&D activities such as (Mönig et al., 2012; Buhmann et al., 2008; Wagner, 2005; Orzechowski, 2018; Kudla and al., 2020; Kreienmeyer et al., 2008). The necessary steps are:

1. Identification of boundary conditions and requirements, including knowledge about the actual site, the repository concept and the safety concept
2. Identify the relevant process classes and corresponding impacts to the EBS based on the FEPs
3. Identify usable construction materials, based on chemical environment and technical feasibility
4. Develop a preliminary design (draft) out of the knowledge grained in (1), (2) and (3) and name the different components
5. Identify the necessary assessments to proof integrity of the EBS
6. Determine dimensions of the barrier and its components
7. Prepare a preliminary or simplified assessment for the most relevant safety functions (commonly hydraulic resistance and mechanical stability)
8. Start a new iteration at (4) if safety function are not met

Sanders (2020) illustrated the named stepwise approach, see Figure 6-1.

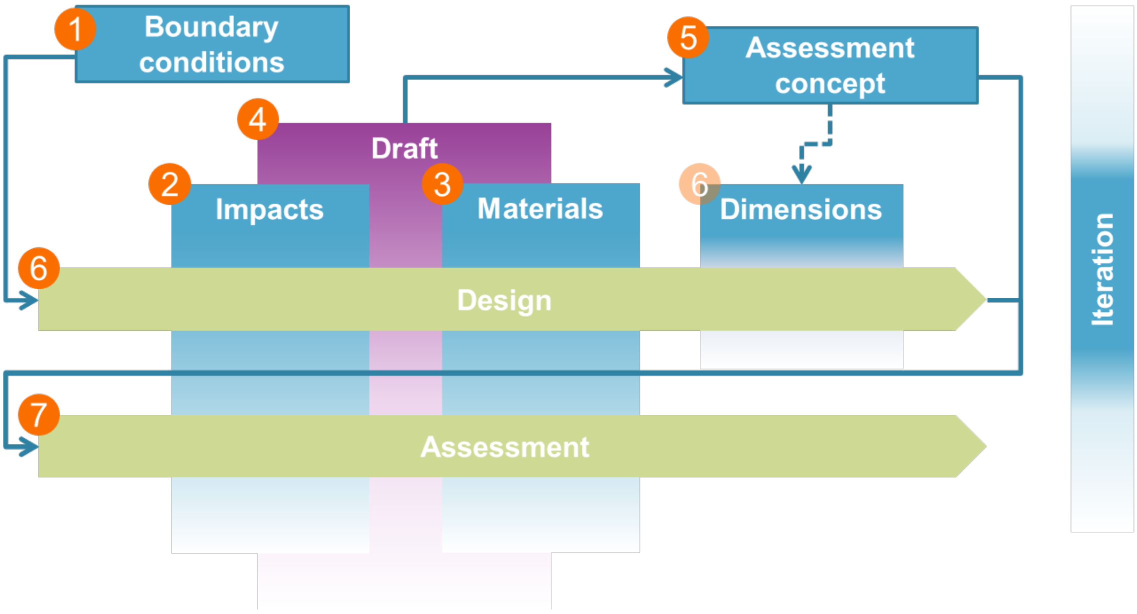

Figure 6-1: Illustration of the design process for EBS, based on Sanders (2020)

The requirements (Position 1 in Figure 6-1) and impacts (Position 2 in 6-1) to the single barrier are derived from the total repository system and allow a formulation of target properties. Thus, a consideration of the entire system is not necessary for the design of the sealing concept or its single elements. Thermal impacts result from the natural rock temperature, operation of the repository (e.g. ventilation) and the thermal output of the radiological decay (of the em-placed waste). With respect to the given temperature limits target properties to the EBS are given e.g. by limiting the hydration temperature of used concrete based materials. Additionally the used materials have to be stable under the given temperature conditions. Hydraulic impacts result from gas or fluid pressure. Hydraulic conductivity represents the corresponding target property. Mechanical impacts are divided in static and dynamic impacts. Static impacts result from the local stress field and potential thermos-mechanical impacts. Dynamic impacts result from earthquakes. Mechanical target properties are e.g. the stiffness of the materials. Chemical impacts are given by the geological setting at the actual sealing location and the expected gases or brines. The composition of them influence the material selection and can result in target properties for chemical composition of the usable materials.

The EBS design process for the RANGERS project considers existing preliminary designs as developed in other R&D projects, too. The transfer of those concepts represent the step (4) of the presented method, see Figure 6-1. The considered shaft sealing concept base on Herold et al. (2020) and a design variation deduced from this. The considered drift sealing concept base on Bollingerfehr et al. (2018) with modifications of the long-term sealing element. All concepts are described in the following sub-sections. The preliminary assessment (6 in Figure 6-1) as well as the full assessment (7 in Figure 6-1) are prepared with the RANGERS project.

6.5 Reference shaft sealing concept for a repository in bedded salt formation

6.5.1 Reference Design

For shaft closure the shaft sealing concept developed within the ELSA 2 project (Herold et al., 2020) and as a second option a slightly modification is considered. Both sealing concepts follow the design principle of complete filling of the shaft column. The main sealing element consists of bentonite (preferably dry-installed binary mixture of briquettes and granulate). Equipotential segments are incorporated into the bentonite sealing element. The following combinations are possible with the bentonite sealing element:

- Bentonite - bitumen/asphalt
- Bentonite - saltclay mixture

A design with combinations of bentonite/clay with bitumen/asphalt is typically used for the closure of conventional mines with solution-filled mine workings. The transition between bitumen and the binary bentonite mixture in the dry initial state is constructed from a low-permeable intermediate layer of compacted fine-grained filler material (e.g. fine sand with limestone powder, 0.1 µm to 1 mm, with a permeability (k) ranging from 10^{-14} m^2 to 10^{-15} m^2). This minimizes both the sinking of the bentonite pellets and powder into the viscous bitumen and the penetration of bitumen into the pore space of the binary mixture. Combinations of the binary bentonite mixture and compacted salt-grit-clay mixture are possible. Table 6-1 summarizes the considered sealing elements and their sealing principles.

Table 6-1: Summary of considered sealing elements, principle of operation and design parameters

Material	Sealing capacity of the material	Contact zone	EDZ
Bitumen / Asphalt	Impermeable for liquids	if bitumen wets the wall and the wetting is maintained during the application of liquid pressure, the contact zone is tight.	Little effect (only if bitumen can penetrate into cracks)
Salt-clay mixtures	Gas permeability $> 10^{-16}$ m^2 Liquid permeability unknown	Influence on contact zone not yet investigated (probably good connection to rock face possible with sufficient compaction)	The installation of the mixture has (probably) no influence on the ALZ but cannot be excluded for dynamic impulse compaction
Bentonite	Liquid permeability $< 10^{-17}$m^2	Swelling pressures of 1 to 2 MPa are possible for Ca-bentonite, provided that εV = 0. For in-situ structures, the swelling pressures depend on the deformations actually occurring.	Reduction of EDZ permeability depending on contact pressure
MgO-concrete (C3, used in ELSA2)	Liquid permeability $2 \cdot 10^{-18}$ to $5 \cdot 10^{-18}$ m^2	Tight connection to rock possible. Influence of the "expansion pressures" of the MgO-concrete not yet sufficiently investigated, as these depend on the possible deformation of the MgO-concrete.	Reduction of the permeability of the ALZ depending on the contact pressure

Starting from the shaft sump, the deepest parts of the shaft as well as the subsurface landing station will be filled with MgO-concrete. In this area the MgO-concrete fulfills abutment function. Above the landing station MgO-concrete is considered as sealing element. In this case recuttig of the shaft contour is possible. In theory, thin asphalt layers or injections (e.g. sodium silicate) can be added to improve sealing function, especially at the contact area but results of the large borehole tests performed in Kudla and al. (2020) as well as experiences at the Asse II mine Heydorn et al. (2016) show that contact gap injections are not required for sealing elements made of MgO-concrete. To guarantee chemical stability of the MgO-concrete a gravel column filled with Mg-salt (e.g. Brucite) is installed above the MgO-concrete. Water intakes from above will be saturated with Mg when it passes the gravel column. The gravel column represents also an abutment for the bentonite sealing element. Above the bentonite a column of compacted salt-clay mixture is installed. The location of the bentonite below the salt-clay mixture should ensure a saturation of intake water with Na and provide a stable chemical composition of the brine entering the bentonite. At the salt top a bitumen filled gravel column will be installed, covering surrounded anhydrite and clay layers too. Table 6-2 summarizes the shaft sealing elements in the shaft, their position and their installation method for the reference shaft sealing concept. Inside the salt formation no shaft liner will remain. Recutting of the contour (extensions of the diameter) are possible. Outside the salt formation and at the slat top, a watertight liner is installed and will remain. In the area of the overburden a simple gravel column will be installed. The following figures 6-2 and 6-3 illustrates the described design. The next table summarizes the sealing properties of the different elements.

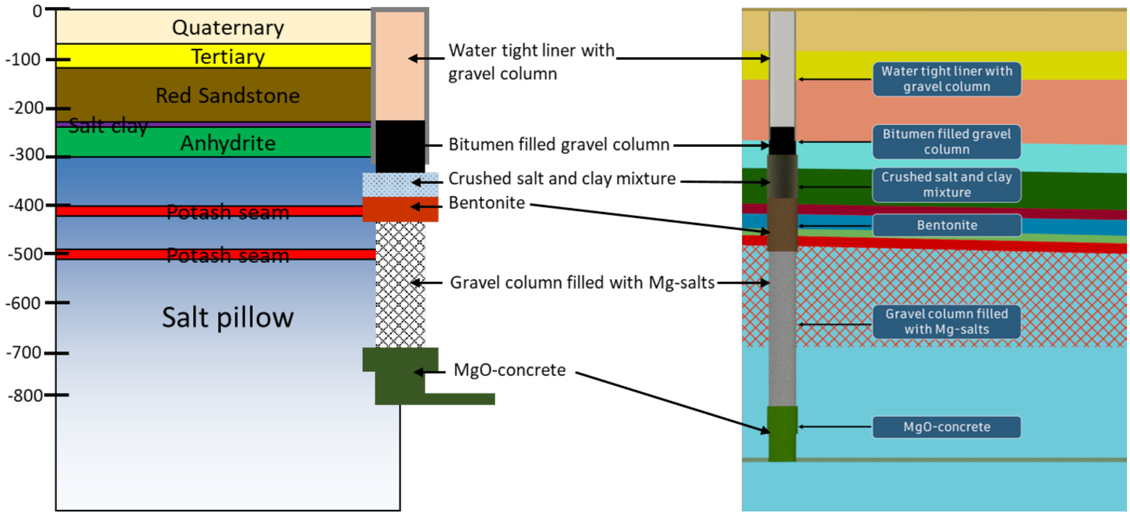

Figure 6-2: Illustration of the shaft sealing concept developed in Herold et al. (2020) (left) and adapted to the actual geological situation at shaft 2 of the the generic reference model (right)

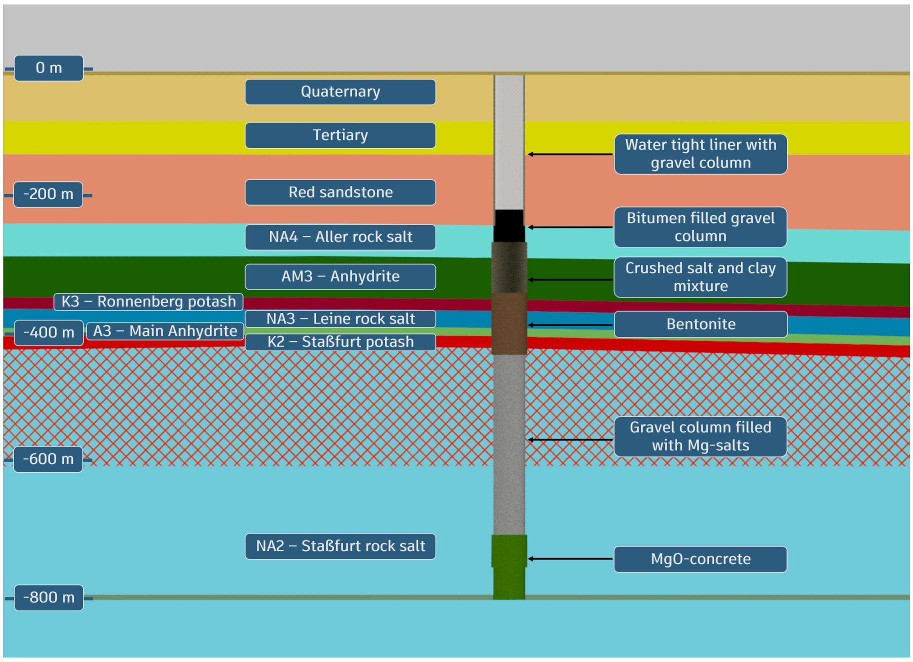

Figure 6-3: Illustration of the shaft sealing concept

Table 6-2: Shaft sealing elements, position, material and installation method for the reference shaft sealing system

Component	Top (depth below surface)	Bottom (depth below surface)	Construction material and installation method
Bitumen-filled gravel column	206	256	Similar to ERAM in-situ test, material properties from ELSA
Crushed-salt-clay-mixture	256	334	Composition from ELSA 2, dynamic impulse compaction
Bentonite	334	429	Ca-Bentonite Type “Saltzdetfurth”, binary mixture with conventional compaction
Gravel column	429	705	Material like VSG, dumping by pipe
MgO-concrete (sealing element)	705	755	Material like VSG, cast in place
MgO-concrete (abutment)	755	805	Material like VSG, cast in place

6.5.2 Optimization or alternative design

Bentonite produces a swelling pressure and creates an active contribution to the sealing as well as healing of the EDZ. Additionally the convergence of the host rock close EDZ over time. The convergence increases with depth. If the bentonite is located in areas with less convergence, the sealing properties could be improved because of the swelling pressure. The optimization of the closure concept include a changed position of the bentonite and crushed salt element. The bentonite will be located closer to the salt top. The crushed salt element below. Unsaturated water is not able to dissolve the bentonite. Table 6-3 summarizes the shaft sealing elements in the shaft, their position and their installation method for the alternative shaft sealing concept. When the water crosses the bentonite over time it will saturate and is not able to solve the crushed salt, see Müller-Hoeppe et al. (2012b). The contact of unsaturated water with bentonite have to be considered during the selection of the bentonite Figure 6-4 and Figure 6-5.

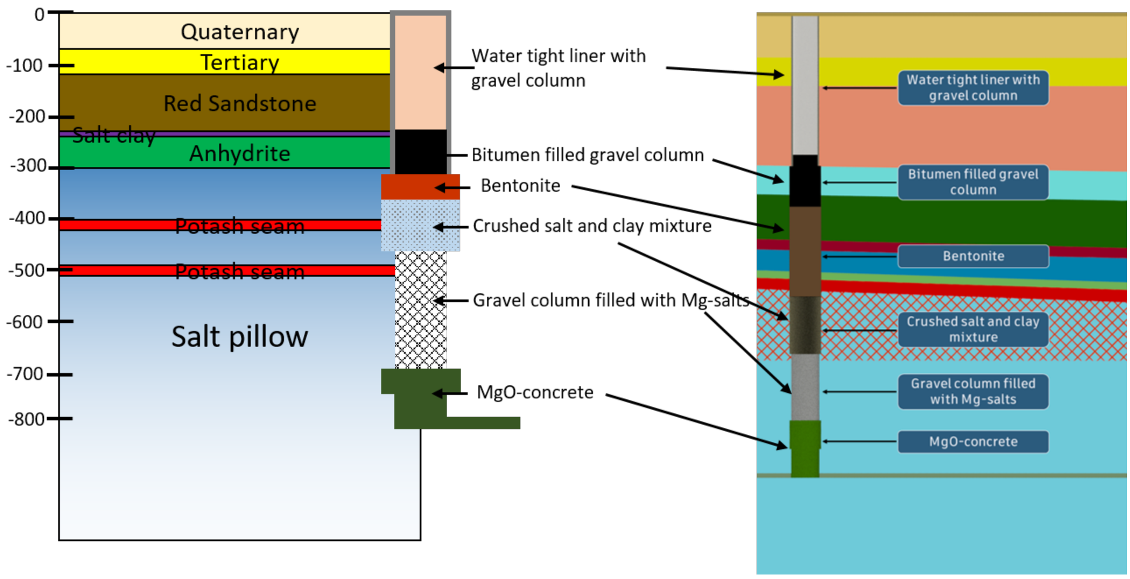

Figure 6-4: Illustration of the alternative shaft sealing concept adapted to the geological situation at shaft 1 of the generic reference model

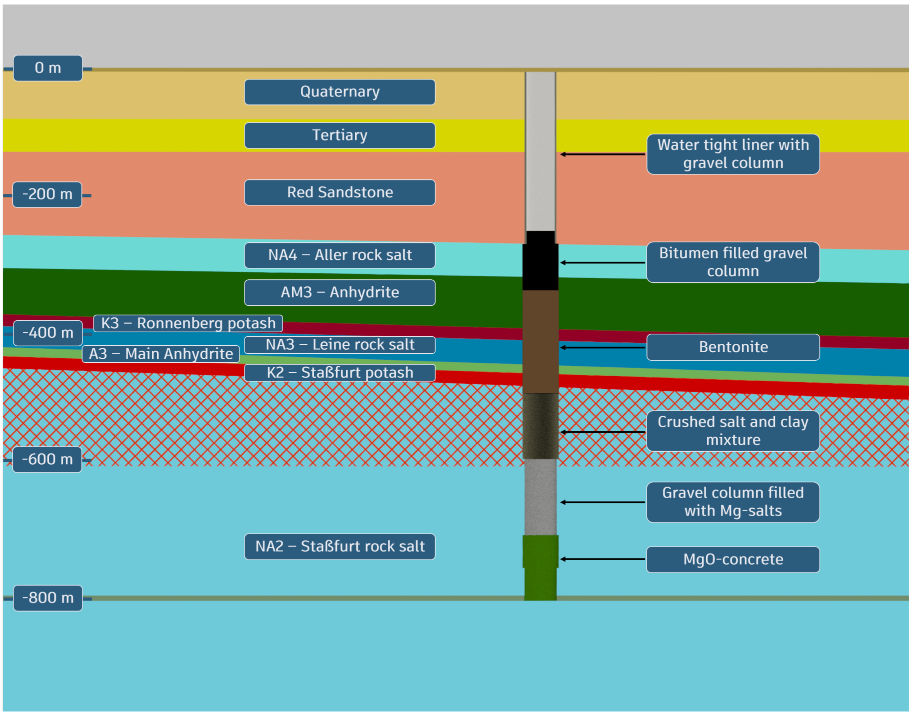

Figure 6-5: Illustration of the alternative shaft sealing concept

Table 6-3: Shaft sealing elements, position, material and installation method for the alternative shaft sealing system

Component	Top (depth below surface)	Bottom (depth below surface)	Construction material and installation method
Bitumen-filled gravel column	241	331	Similar to ERAM in-situ test, material properties from ELSA
Bentonite	331	488	Ca-Bentonite Type Saltzdetfurth, binary mixture with conventional compaction
Crushed salt-clay mixture	488	588	Composition from ELSA 2, dynamic impulse compaction
Gravel column	588	705	Material like VSG, dumping by pipe
MgO-concrete (sealing element)	705	755	Material like VSG, cast in place
MgO-concrete (abutment)	755	805	Material like VSG, cast in place

The location of the two shaft sealing systems in the geological formation is illustrated in 6-6.

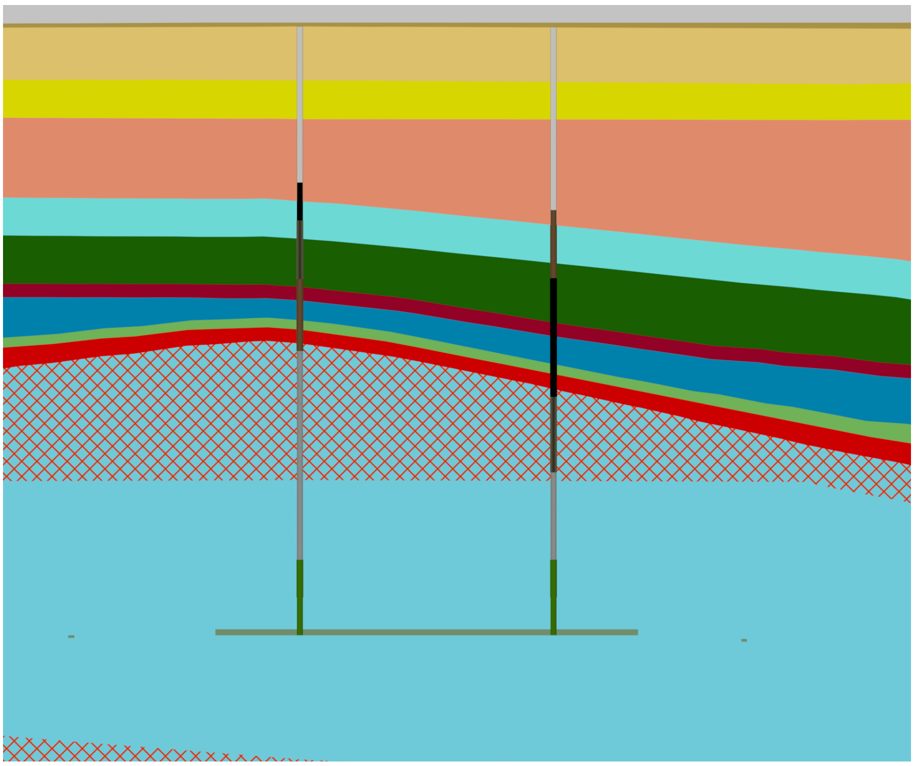

Figure 6-6: Illustration of both shaft sealing concepts in the geological model used in RANGERS

6.6 Reference drift sealing concept for a HLW-repository in salt

Conceptual designs for drift sealing in HLW/SF repositories are presented in Müller-Hoeppe et al. (2012b); Bollingerfehr et al. (2018). Practical experiences in the construction of drift seals made of concrete are known e.g. from Asse II mine, see Heydorn et al. (2016); Meyer et al. (2019); Köhler et al. (2019).

The drift seals, as designed for the Gorleben site, considers two sealing elements made of MgO-concrete. Both are covered by concrete based abutments to guarantee mechanical and local stability. All elements are placed in a row and with direct contact, Figure 6-7. Bollingerfehr et al. (2018) consider in principle the same design, including concrete based sealing elements and abutments. In between the sequence of sealing elements and abutments, an additional long-term sealing element is considered. For a length of 300 m the drift has to be backfilled with crushed rock salt. “The compaction of the crushed salt, which is driven by salt creep, results in a very low permeability of the crushed salt over a certain period of time. Evidence must be provided that sealing by the compacted backfill material is fully developed by the time the performance of the engineered barriers can no longer be demonstrated” (Bollingerfehr et al., 2018).

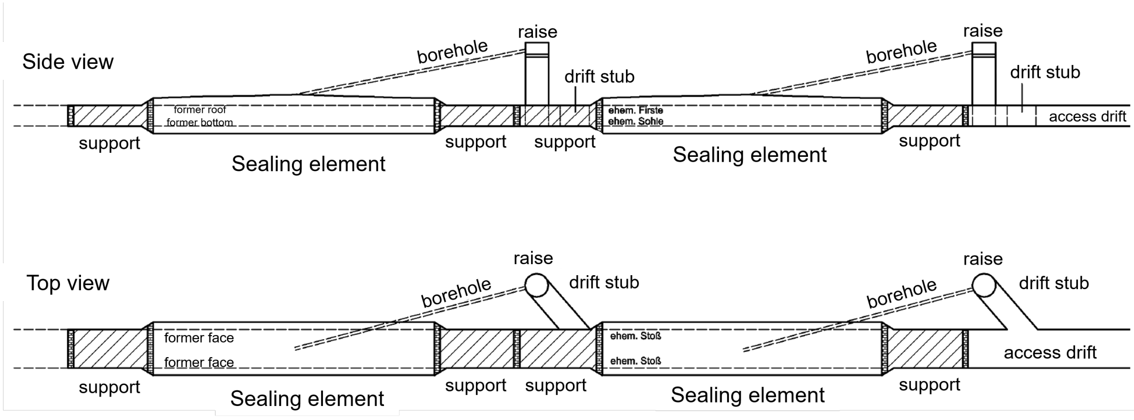

Figure 6-7: Conceptual design of the drift seal in Müller-Hoeppe et al. (2012b)

In common mining and as well in Asse II mine the filling of concrete based sealing elements is typically done by drilling starting from an upper mine level and ending inside the sealing location. Inside the generic repository design only one mine level exists. The upwards directed raise (see Figure 3 16) was proposed by is used to provide a sufficient height difference for the filling of the sealing elements and allow an as high as possible filling grade. Additionally the roof of the sealing element is cone-shaped in direction to the wells. The wells end at the highest point of the roof in the middle of the sealing element. It is already demonstrated that the spreading behavior of MgO-concrete during concreting is given up to about 25 m (Müller-Hoeppe et al., 2012b). The total length of the sealing is limited to 50 m. From the middle of the seal the concrete can flow to both directions.

Using a raise and cope-shape roof represent a high additional technical effort during construction of the sealing. To simplify the construction it is proposed to implement an inclination at the sealing location, already during excavation. Highest point of the drift segment have to be located at the shaft side. Concreting will be done from this side. The flow angle of MgO-concrete

(e.g., A1-mixture form Asse II mine (Müller-Hoeppe et al., 2012b)) is approximately 1.2°. If the drift has an inclination of 1.5° concreting can be done without the raise and a cone-shape roof. The establishment of air pockets due to locally larger flow angles or roughness of the roof can be avoided by concreting under pressure.

To enhance the speed of compaction of the crushed salt in the designated area of the long-term seal, it is moistened before backfilling. The effect of accelerated creep of moistened crushed rock salt was demonstrated successfully in laboratory scale

7 FEPs and Scenarios for EBS

7.1 Fundamentals

7.1.1 Linkage between integrity proof of EBS and FEP / scenarios

The methodology for integrity proof of the Engineered Barrier system (EBS) is fixed in technical regulations and has to be linked with the methodology for long term safety assessment (incl. FEP and scenarios). Therefore the impacts, loads and load resistances as well as design situations of the technical functional proof have to be assigned to FEP and scenarios. Thus components of the geotechnical barriers can be dimensioned using the partial safety factors method.

In the R&D project RANGERS, two categories of FEP lists as descriptions of repository system evolution are provided:

- a more general FEP list giving a comprehensive description of repository system and
- two specific FEP lists for the nearfield of the geotechnical barriers

The compilation of a comprehensive FEP catalog for a repository system is a quite extensive task and exceeds the scope and purpose of the RANGERS project. Therefore it is obligatory to rely on the FEP catalog and the combined scenarios from a former project as an example. For Germany, the only adequate project on HLW-disposal in a salt dome structure is the Preliminary Safety Assessment for the Gorleben Salt Dome (VSG) (Wolf et al., 2012). For US only generic studies on HLW disposal in salt formations are available.

One objective of the project was to analyze an existing generic numerical model of a salt pillow that has been developed for the R&D project KOSINA (Völkner et al., 2017b). The geological structure of this model differs from the structure of the Gorleben salt dome, but the geological formations are identical and the layout of the repository mine with drift emplacement is similar. For the KOSINA project, neither a FEP catalog nor a scenario development have been prepared. But in principle, FEP catalogs for HLW repositories in salt formations are quite similar. There are only very few FEP that are site specific and not relevant for other sites. Differences only become apparent when details of specific characteristics of features or processes are analyzed. The main objective of the RANGERS project is to develop a methodology and procedure for performance assessment as well as to test their applicability and functionality. Therefore an exemplary investigation has to be done and some small discrepancies between the description of the repository system and its evolution and the numerical model are tolerable.

The descriptions of the RANGERS FEP will be done on a very general level and site-specific FEP of the Gorleben salt dome, that are not relevant for the KOSINA model, will be excluded.

The more detailed FEP lists for the nearfield of the geotechnical barriers have been adapted and specified according to the requirements of the EBS performance assessment.

7.1.2 Features, Events and Processes

A FEP list gives a summary of features characterizing the initial properties of a repository system at the end of the operational period and relevant information on events and processes which might influence the future evolution of the repository system. In the context of a safety assessment, the FEP list is highly relevant as it is the connecting link between the fundamentals (site description, geoscientific long-term prognosis and radioactive waste inventory), the repository concept, and the system analysis. Apart from the compilation of the most relevant basics, the FEP list reflects the interrelation between the site specific conditions and the modifications resulting from the disposal of radioactive waste. Therefore it is a sound basis for scenario development, for process analyses, for demonstrating the integrity of geological and geotechnical barriers and for the analysis of the radiological consequences. In the context of the RANGERS requirements, first a comprehensive FEP-list for the whole repository system has to be considered. For specific analysis of the boundary conditions in the nearfield of the geotechnical barriers it is useful to extract specific, detailed FEP lists for the corresponding subsystems.

The German state-of-the-art in FEPs and Senarios has been developed in R&D projects ISIBEL / VSG (Bollingerfehr et al., 2013) and ANSICHT (Lommerzheim et al., 2019) as well as most recently in the documents for the license application for closure of the ERAM repository (not yet published). Objectives for the methodology are to reflect all relevant future evolutions as comprehensively as possible. Furthermore scenarios will be derived systematically and transparently from the FEP catalog. Measures to increase completeness of a FEP list are:

- a comparison with the NEA-FEP database which is a compilation of numerous international FEP lists from different host rocks,
- bottom-up and top-down approaches to identify relevant FEP,
- plausibility checks of the sequences and inter-dependencies of the FEPs as well as
- consideration of indications from the geoscientific long-term prognosis, the scenario development and the process analyses.

Basic principle for all FEP lists (incl. the NEA-FEP-list) is their composition from two major FEP-groups:

- the “features” or “components”, that describe all elements of the repository system, and
- the “processes” (and “events”), that affect the components and describe the future evolution of the repository system.

With regard to the definition of FEP there is a broad scope of discretion: e.g. it is possible to describe one component in one FEP or to define each element or each property of the component in a separate FEP. So the NEA-FEP-list is very detailed with a high degree of itemization. In German projects, an intention was to define FEP in such a manner that the FEP are clearly separated and overlaps are avoided. Furthermore “components” including their proper-ties are completely described in one FEP. Looking at the interaction between the FEP in causal sequences, a direct interaction between two “components” is not possible, but only via connecting “processes”. So a “process” may influence the properties of a “component”, and vice versa (e.g. the process “concrete corrosion” modifies the chemical, mechanical and hydraulic properties of the component “drift seal” and, conversely, the chemical and hydraulic properties of the "drift seal" influence the intensity of "concrete corrosion").

Two FEP-categories, that are parts of the NEA-FEP-list, were excluded from the German-FEP-lists due to regulatory reasons: “features/processes of the biosphere” and “future human actions”. A basic reason is, that neither a prognosis of the future biosphere nor of future human actions is possible and therefore corresponding FEP cannot be defined. The assessment of radionuclide release in future biosphere and the evaluation of potential human intrusion scenarios will be handled by stylized scenarios defined by the regulator.

7.2 Description of repository system by FEP

To be comparable with the US data for layered salt formations, the RANGERS project relies on data for the KOSINA project that focused on layered and pillow-like salt formations. Geology, repository concept and numerical models are described in chapters 4 and 5. But neither for this geology nor for that repository concept a FEP catalog has been developed in the KOSINA project. Due to the limited capacity in the RANGERS project it was not possible to develop a special FEP catalog for German flat bedded salt formations. Therefore the FEP catalog relies on the VSG FEP catalog with exchange of Gorleben specific FEPs by KOSINA specific FEPs. Looking at the RANGERS specific tasks, the repository system description has been restricted to a FEP list with a short description of the FEP meaning. The dependencies between the FEP are not given here but can be from the VSG FEP catalog (Wolf et al., 2012). The structure of the FEP catalog has been updated to the recent state-of-art as given by the ANSICHT (Krull et al., 2004; Reinhold et al., 2008; Völkner et al., 2017a; Liu et al., 2017) and ERAM projects (not yet published), see table 7-1.

Table 7-1: FEP-list of the RANGERS-specific repository system in a salt pillow

FEP No	FEP Name	Description
Processes with direct impact on EBS function (= Initial-FEP) are red marked.		
Processes with impact on radionuclides mobilization and transport are green marked		
Compartment Geosphere		
Features		
2.2.02.01	Host rock	Describes the chemical, hydraulic, mechanical and thermal properties of the host rock at the time of repository closure (Völkner et al. 2017). Salt pillar includes Staßfurt, Leine, Aller and Ohre formations. thickness of disposal formation (Hauptsalz) up to 600 m at repository level
2.2.02.02	Faults and joints in the host rock	Describes the chemical, hydraulic, mechanical and thermal properties of the faults and joints in the host rock (Völkner et al. 2017). They are relevant for carbonate, anhydrite and clay formations.
2.2.03.01	Adjacent rocks	Describes the chemical, hydraulic, mechanical and thermal properties of over (Bunter, Tertiary, Quaternary) and underlying (Red Formation) rocks at the time of repository closure (Völkner et al. 2017).

FEP No	FEP Name	Description
2.2.04.01	Faults and joints in the adjacent rocks	Describes the chemical, hydraulic, mechanical and thermal properties of the faults and joints in the adjacent rocks (Völkner et al. 2017). Important in consolidated rocks (Bunter, Red Formation)
2.2.07.01	Fluids in the host rock	describes the quantities and the chemical properties of brine and hydrocarbons in the intergranular crystall framework. Furthermore fluids are often accumulated in faults and joints of anhydrite and carbonate layers and due to permeation processes they may intrude from the top of salt formation or underlying formations (Liu et al. 2018)
2.2.07.02	Gas in the host rock	describes the quantities and the chemical properties of free gases or adsorbed gases at crystal boundaries and gaseous hydrocarbons. Furthermore gases are often accumulated in faults and joints of anhydrite and carbonate layers and due to permeation processes they may intrude from the top of salt formation or underlying formations (Liu et al. 2018)
2.2.08.01	Fluids in the adjacent rocks	describes the quantities and the chemical properties of pore water and water on faults and joints of competent formations (Liu et al. 2018).
2.2.08.02	Gas in the adjacent rocks	describes the quantities and the chemical properties of free gases or adsorbed gases in pores and gaseous hydrocarbons (Liu et al. 2018)
2.3.01.01	Geomorphology	The relief and shape of the surface environment and its potential evolution with time
2.3.04.01	Surface Water	Characteristics of rivers and lakes and their potential evolution
Events and Processes		
Geologic and climatic processes		
1.2.01.01	Neotectonic movements	Describes recent tectonic movements resulting in deformations in geosphere that characterize the recent stress field of the region.
1.2.01.03	Vertical movements of lithosphere	Describes very slow, large-scale epirogenetic movements (up or down-lift) of the lithosphere due to the underlying movement of the crustal plates.
1.2.02.01	Crustal deformation	Describes deformations of geosphere that are not caused crustal plate movements, e.g. isostatic movements
1.2.03.01	Earth quake	Release of accumulated geologic stress via rapid relative movements in the geosphere
1.2.07.01	Erosion	Include processes for disintegration of sediments and transport of erosion products.
1.2.07.02	Sedimentation	Deposition of particles from a transport medium.
1.2.08.01	Diagenesis	Transformation of sediments by compaction, cementation and crystallization.
1.2.09.01	Salt diapirism	Uplift of salt formations from deep geological levels due to high overburden pressure, fractures and tectonic movements, thick salt formations and low density of salt.
1.2.09.02	Subrosion	Salt solution at contact between unsaturated groundwater and salt formations
1.3.01.01	Global climate change	Long term evolution of climate

FEP No	FEP Name	Description
1.3.03.01	Transgression and regression	Offshore or onshore relocation of the coast line.
1.3.04.01	Permafrost	Permanent freezing of soil and near surface rock formation during glacial periods
1.3.04.02	Cryogenic fractures	Fractures in soil and near surface rock formations due to climate induced freezing and resulting thermo-mechanical stresses
1.3.05.01	Effects of glaciers and ice sheets	Includes processes like exaration (glacial erosion) and glacial loading
1.3.05.03	Periglacial channeling	Below a glacier, melting water may erode glacial channels.
1.5.03.01	Pathways in exploration drillings	Channeling in a borehole seal
Mechanical processes		
2.2.06.01	Mechanical stress changes	Describes the transition of tension resulting from an increase or decrease of tension in the rocks or a component of the repository.
Hydraulic processes		
2.1.07.02	Fluid pressure change	Describes a change of fluid pressure because of changes of tension in components / rocks or fluid flow processes.
2.2.07.03	Groundwater flow in the overburden rock	Describes the liquid flow in overburden rock because of potential gradients.
2.2.07.04	Gas flow in the overburden rock	Describes the liquid flow in overburden rock because of potential gradients.
2.2.07.05	Groundwater flow in the host rock	Describes the liquid flow in host rock because of potential gradients.
2.2.07.06	Gas flow in the host rock	Describes the liquid flow in host rock because of potential gradients.
2.2.08.01	Liquid-mediated transport of radionuclides	Summarizes all kind of transport processes of radionuclides in liquids
2.2.08.02	Gas-mediated transport of radionuclides	Summarizes all kind of transport processes of radionuclides in gases
Chemical-microbiological processes		
2.1.09.02	Dissolution and precipitation of salt minerals	Dissolution describes transition from solid phase to liquid. Precipitation is the inverse process.
2.2.09.01	Microbial processes in the host rock and the overburden formations	Summarizes all microbial processes in the host rock and in the adjacent rocks.
Thermal processes		
2.2.10.01	Thermally-induced uplift of the overburden rock	Uplift of salt formation and overburden rocks due to thermally induced volume changes
2.2.10.02	Thermal expansion or contraction	Volume change resulting from temperature change.
2.2.10.03	Heat flow	Temperatures in geosphere are influenced by geothermal, climate and heat generating waste
Compartment: Shafts, infrastructure area and connecting drifts		
Features		
2.1.04.01	Backfill	Describes the chemical, hydraulic, mechanical and thermal properties of the backfill at the time of repository closure (Bertrams et al. 2018).
2.1.05.01	Borehole seals	Describes the chemical, hydraulic, mechanical and thermal properties of borehole seals for exploration drillings at the time of repository.

FEP No	FEP Name	Description
2.1.05.02	Shaft seals	Describes the chemical, hydraulic, mechanical and thermal properties of the shaft seal at the time of repository closure. The contact zone *) has been enclosed in the FEP (chapt. 3.5.3).
2.1.05.03	Drift seals	Describes the chemical, hydraulic, mechanical and thermal properties of a drift seal at the time of repository closure (Bertrams et al. 2018). The contact zone *) has been enclosed in the FEP. (Chapt. 3.5.4)
2.1.06.01	Technical installations	Installations remaining in the repository after closure, e.g. rock bolts, cables, shaft/drift lining *), roadway etc. and summarizes their properties
2.1.08.03	Liquids in mine excavations	describes the quantities and the chemical properties of liquids from waste, from construction material and from inflow of the surrounding rocks or via the shafts/ramp
2.1.12.02	Gas in mine excavations	describes the quantities and the chemical properties of mine air and gas from metal corrosion and microbial degradation of organic matters and from inflow of the surrounding rocks
2.2.01.01	Excavation disturbed zone (EDZ)	Tension redistribution in the geosphere results in the disintegration of a rock zone close to the mine openings. This FEP also includes concrete injections *) to reduce the hydraulic conductivity of EDZ.
		\) separate FEP in subsystem description (chap. 6.3) for detailed analysis
Processes		
Mechanical processes		
2.2.06.01	Mechanical stress changes	Describes the transition of tension resulting from an increase or decrease of tension in the rocks or a component of the repository.
2.2.06.02	Convergence	Reduction of void volume by rock creeping.
2.1.07.03	Compaction of crushed salt	Describes the slow consolidation of crushed salt. Compaction results in a solidification and a reduction of porosity. Initiating processes are gravity forces and the load from surrounding geosphere.
2.1.07.04	Swelling, shrinking and creeping of concrete	Describes not thermal induced volume or pressure changes of concrete.
2.1.08.08	Swelling and shrinking of bentonite	Means the adsorption and release of water from the crystal interim layer of clay minerals
2.1.07.07	Displacement of the shaft seals	Describes a change of seal position in comparison with construction site
Hydraulic processes		
2.1.07.02	Fluid pressure change	Describes a change of fluid pressure because of changes of tension in components / rocks or fluid flow processes.
2.1.08.06	Liquid intrusion into mine excavations	Inflow of liquid from host rock or adjacent formations
2.1.08.07	Liquid flow in mine excavations	Describes the liquid flow because of potential gradients.
2.1.08.08	Gas flow in mine excavations	Describes gas flow because of potential gradients
2.1.08.04	Channeling in crushed salt	Generation of flow paths by inhomogeneous compaction or swelling or erosion of backfill

FEP No	FEP Name	Description
2.1.08.05	Channeling in sealing components	Generation of flow paths by inhomogeneous compaction or swelling or erosion of concrete / bentonite
2.2.07.01	Liquid-mediated transport of radionuclides	Summarizes all kind of transport processes of radionuclides in liquids
2.2.07.02	Gas-mediated transport of radionuclides	Summarizes all kind of transport processes of radionuclides in gases
Chemical-microbiological processes		
2.1.09.02	Dissolution and precipitation of salt minerals	Dissolution describes transition from solid phase to liquid. Precipitation is the inverse process.
2.1.09.03	Corrosion of metal	Describes the electrochemical reaction of metals with surrounding fluids and resulting gas generation
2.1.09.06	Corrosion of cement- or sorel-based materials	Describes the chemical degradation of concrete
2.1.09.07	Solution, transformation and regeneration of clay minerals	Describes the mineralogical and chemical transformation of clay minerals (in shaft seals) due to changes in hydrochemistry
2.1.09.08	Alteration of Anhydrite and Gypsum formation	Anhydrite (water-free Ca sulfate) is alterated by water with formation of gypsum (Ca sulfate-Dihydrate). In the course of this exothermal reaction, the volume of the solid phase significantly increases.
2.1.10.02	Microbial processes in the repository	Summarizes all microbial processes in the mine excavations including the EDZ.
Events		
2.1.07.05	Early failure of integrity of a shaft seal	Failure of a shaft seal during the functional lifetime by chemical, mechanical, hydraulic or thermal impacts.
2.1.07.06	Early failure of integrity of a drift seal	Failure of a drift seal during the functional lifetime by chemical, mechanical, hydraulic or thermal impacts.
Compartment: disposal areas		
Features		
2.1.01.01	Inventory: Radionuclides	compiles the composition, activity and quantities of the radionuclides enclosed in the radioactive waste at the time of emplacement. (Bertrams et al. 2015)
2.1.01.02	Inventory: Metal compounds	compiles the chemical composition and quantities of all metal components in the repository mine (Bertrams et al. 2015)
2.1.01.03	Inventory: Organic compounds	compiles the chemical and microbial composition and quantities of all organic matter in the repository mine (Bertrams et al. 2015)
2.1.01.04	Inventory: Other compounds	compiles the chemical composition and quantities of other materials in the repository mine (e.g. graphite (for AVR/THTR spent fuel and neutron moderator of disposal casks), concrete for mine installations and geotechnical barriers) (Bertrams et al. 2015, 2018)
2.1.02.01	Waste matrices	Describes the chemical, hydraulic, mechanical and thermal l properties of the waste matrices (e.g. metal, borosilicate glass) at the time of emplacement (Bertrams et al. 2015).
2.1.03.01	Spent fuel containers	Describes the composition and properties of POLLUX and CASTOR casks that ensure the waste containment during the operation period and at least 500 a during the post closure phase (Bertrams et al. 2015).

FEP No	FEP Name	Description
2.1.03.02	Other disposal containers	Describes the composition and properties of POLLUX and CASTOR casks for reprocessing waste and MOSAIK cask for structural parts from conditioning of spent fuel elements that ensure the waste containment during the operation period and at least 500 a during the post closure phase (Bertrams et al. 2015)
2.1.08.03	Liquids in mine excavations	describes the quantities and the chemical properties of liquids from waste, from con-struction material and from inflow of the host rock (Liu et al. 2018)
2.1.12.02	Gases in mine excavations	describes the quantities and the chemical properties of mine air and gas from metal corrosion and microbial degradation of organic matters and from inflow of the host rock (Liu et al. 2018)
Mechanical processes		
2.2.06.01	Mechanical stress changes	Describes the transition of tension resulting from an increase or decrease of tension in the adjacent rock or a component of the repository.
2.1.07.01	Convergence	Reduction of void volume by rock creeping.
2.1.07.03	Compaction of crushed salt	Describes the slow consolidation of crushed salt. Compaction results in a solidification and a reduction of porosity. Initiating processes are gravity forces and the load from surrounding geosphere.
Hydraulic processes		
2.1.07.02	Fluid pressure change	Describes a change of fluid pressure because of changes of tension in components / rocks or fluid flow processes.
2.1.08.06	Liquid intrusion into mine excavations	Inflow of liquid from the host rock
2.1.08.07	Liquid flow in mine excavations	Describes the liquid flow because of potential gradients.
2.1.08.08	Gas flow in mine excavations	Describes gas flow because of potential gradients
2.1.08.04	Channeling in crushed salt	Generation of flow paths by inhomogeneous compaction or swelling or erosion of backfill
2.2.11.01	Pressure-induced fluid infiltration into the salt rock	If fluid pressure exceeds the smallest main stress in salt rock, the permeability will be locally increased by expansion of the pore structure and fluids can infiltrate the rock.
3.2.07.01	Liquid-mediated transport of radionuclides	Summarizes all kind of transport processes of radionuclides in liquids
3.2.07.02	Advection	Transport of dissolved substances by fluid flow
3.2.07.03	Dispersion	Distribution of dissolved substances by inhomogeneous flow velocities in porous media.
3.2.07.04	Diffusion	Stirring of different substances by BROWN molecular movements
3.2.08.01	Lifting or sinking of waste packages	Compilation of processes that may result in a displacement of waste packages from their emplacement position.
3.2.09.01	Gas-mediated transport of radionuclides	Summarizes all kind of transport processes of radionuclides in gases
Thermal processes		
2.1.11.01	Heat flow	Means the energy transport as a result of temperature differences.
2.1.11.02	Thermal expansion or contraction	Volume change resulting from temperature change.

FEP No	FEP Name	Description
2.1.11.03	Vaporisation of water	Describes the transition from liquid to gas depending from the composition of the liquidl, the pressure and the temperature
2.2.10.02	Thermomigration	Migration of liquid the host rock induced by the temperature field in the surroundings of the disposal areas.
2.2.10.03	Thermal degradation of carnallite	Carnallite has a high content of crystal water that will be released with increasing temperatures at several hydration steps
2.2.10.05	Thermochemical sulfate reduction	Redox reaction of organic matters or molecular hydrogen with sulfate at high temperatures generating carbonate, sulfide, water, hydrogen sulfide or carbon dioxide.
Chemical-biological processes		
2.1.09.02	Dissolution and precipitation of salt minerals	Solid material may be partly or completely dissolved. For halite it will be a congruent dissolution, for complex salt minerals or construction or waste materials it may be an incongruent dissolution. If solubility limits are exceeded, dissolved materials may precipitate.
2.1.09.03	Corrosion of metal	Describes the electrochemical reaction of metals with surrounding fluids and resulting gas generation. If contaminated metal components (e.g. waste canisters, structural part from spent fuel conditioning,) the process contributes to RN mobilization
2.1.09.04	Corrosion of spent fuel	Chemical processes resulting in a degradation of the spent fuel matrix
2.1.09.05	Corrosion of glass	Chemical alteration of the borosilicate matrix of reprocessing waste by interaction with liquids
2.1.09.06	Corrosion of cement- or sorel-based materials	Describes the chemical degradation of concrete
2.1.09.07	Corrosion of graphite waste	Chemical alteration of the graphite matrix of research reactor fuel and moderator/reflector material by interaction with liquids
2.1.09.08	Hydrogen induced embrittlement	The intrusion of hydrogen in metal structures results in a modification of the mechanical properties.
2.1.10.01	Degradation of organic compounds	Describes the alteration of man-made (waste, cables, pipes etc.) and natural organics by chemical processes
2.1.10.02	Microbial processes in the repository	Summarizes all microbial processes in the mine and in the surrounding rocks
3.2.03.01	Sorption and desorption	Sorption describes the physico-chemical interaction of dissolved species with a solid phase. Desorption is the opposite effect.
3.2.04.01	Colloids	Generation of colloids and their filtration during transport
3.2.05.01	Complexation	Impact of complexing agents on the radioactive waste
2.1.12.04	Deflagration and explosion of gases	Mixtures of ignitiable gases and oxygen can deflagrate or detonate if lighted
Radiological Processes		
2.1.13.01	Radiation-induced activation	Generation of radioactive isotopes due to nuclear reaction after absorption of neutrons

FEP No	FEP Name	Description
2.1.13.03	Radiolysis	Radiolysis of water within a waste package can produce hydrogen, oxygen and hydroxide peroxide.
2.1.14.01	Nuclear criticality	Fissile substances are arranged in such a manner that a self-preserving nuclear reaction can take place.
3.1.01.01	Radioactive decay and ionizing radiation	Spontaneous transformation of instable atomic nuclei combined with the emission of characteristically ionizing radiation
3.2.01.01	Mobilization of radionuclides	The processes that directly affect the mobilization of radionuclides from the waste form once the waste container has failed
Events		
2.1.03.03	Failure of a spent fuel container	Failure of waste container as a consequence of undetected construction failures or impact of chemical, mechanical, hydraulic or thermal processes with design exceeding intensity during the functional period.(500 a). Starting point for RN mobiliozation
2.1.03.04	Failure of another waste container	Failure of waste container as a consequence of undetected construction failures or impact of chemical, mechanical, hydraulic or thermal processes with design exceeding intensity during the functional period.(500 a). Starting point for RN mobiliozation

7.3 Description of subsystems

For detailed investigations on EBS design and integrity a precise description of the surroundings of EBS (subsystem) and of all included components as well as the identification of processes that directly impair the EBS are necessary.

For characterization of the components material properties (mineralogy, geochemistry, density, solubility, plasticity, heat conductivity, porosity, permeability, effective strength etc.), construction properties (e.g. volume, geometry (length, width and high), surface properties, fissures etc.) as well as state variables (e.g. temperature, effective strength, microbes etc.) have to be analyzed.

To evaluate the loads that are impacting the EBS, the properties and intensity of the affecting FEP (called initial FEP) have to be determined by analyzing all components and processes that influence those FEP. In this context the FEP list can identify the interacting FEP and describe them qualitatively. To specify the properties and the intensity of processes, numerical process analyses are necessary.

7.3.1 Subsystem Nearfield of Shaft Seal

The subsystem “nearfield of shaft seal” is part of the compartment “Shafts, infrastructures and connecting drifts” (see table 7-1). It comprises the shaft column (incl. EDZ), the construction materials (incl. corrosion materials), fluids, all shaft installations (incl. seals, backfill, lining) and the shaft landing (Herold et al., 2020) as well as adjacent parts of the geosphere and biosphere (Keller et al., 2021), see , see Figure 7-1. The components of the nearfield are influenced by numerous mechanical, hydraulic, chemical and thermal processes initiated in the farfield. So mechanical loads not only result from lithostatic pressure but from modifications of geosphere stress field by tectonic movements (e.g. subsidence, uplift), earth quake or processes like glaciation, erosion and sedimentation. Because this subsystem cuts through the whole geological sequence, not only the host rock but also the aquifers in the overburden formations and the underground facilities are linked. Therefore a broad spectrum of hydraulic impacts is possible – from the overburden, anhydrite reservoirs and brine pockets in the salt formations and fluids that are squeezed out from the underground excavation via the infrastructure area to the shafts. Therefore liquids with a broad spectrum of hydrochemical properties have to be considered and different levels of fluid pressure. Intensive gas generation due to metal corrosion may significantly increase fluid pressure. Due to the distance between the disposal areas and the shafts there will be only a limited increase of temperature but significant thermomechemical stresses may occur. A compilation and short description of all relevant FEP of the subsystem is given in table 7-2. For processes their potential impact on EBS as well as an itemization of affected components is given. FEPs that are excluded in a screening process due to their low probability and/or intensity are not mentioned.

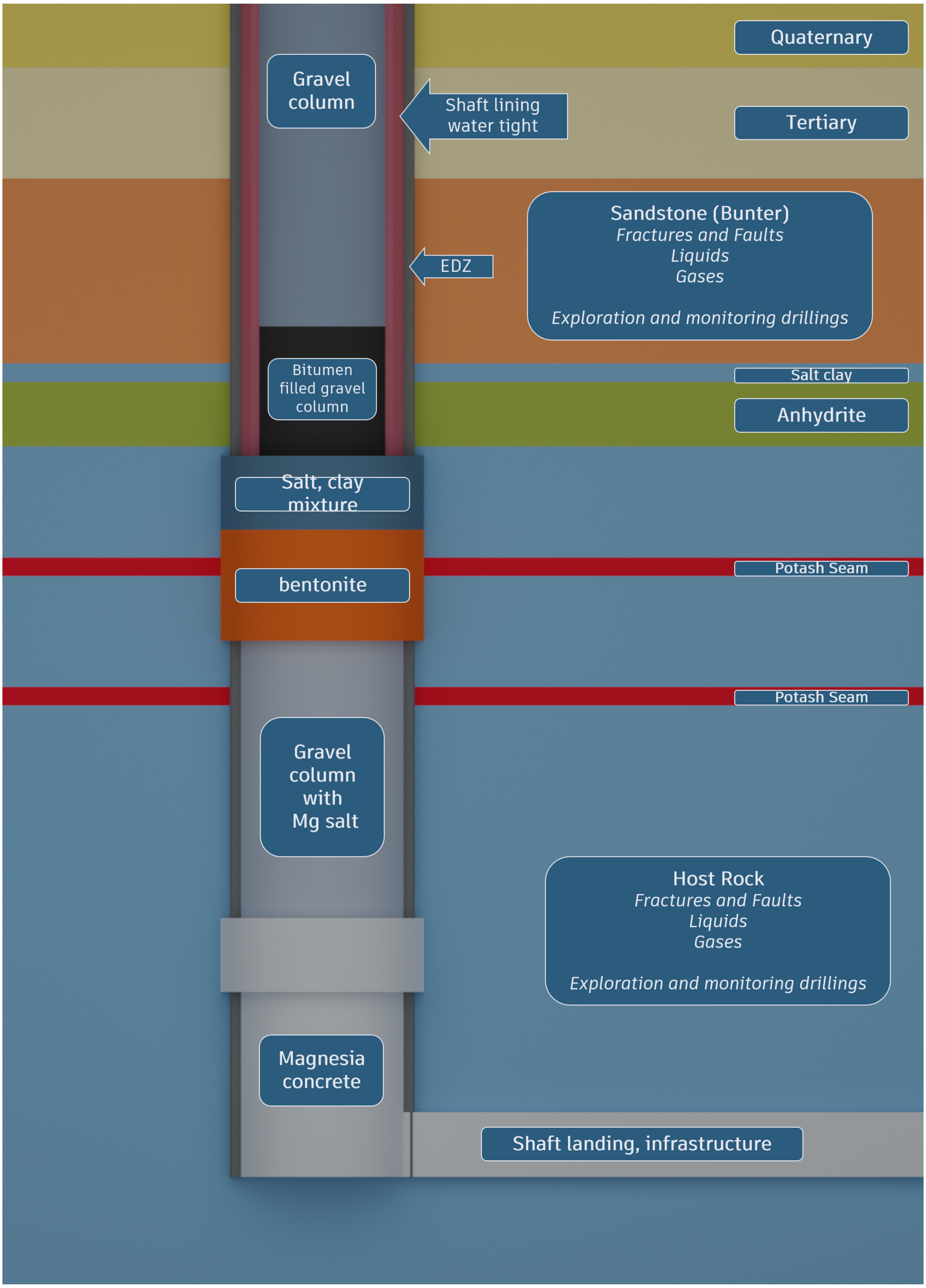

Figure 7-1: Nearfield model for the shaft seal, FEP in italics

Table 7-2: FEP lists for the subsystem "Shaft seal". Processes that may directly affect the EBS function (Initial FEP) are red marked.

					Components affected by processes																			
Subsystem Shaft	**Process Group**	**FEP (No. referring to the components mentioned in right column)**	**Description**	**Direct impact of processes on barrier function and other shaft components**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Components		1 Shaft seal	Describes the chemical, hydraulic, mechanical and thermal properties of the shaft seal at the time of repository closure. Shaft seals consist of abutments and sealing elements. The construction materials (salt concrete, magnesia concrete, bentonite, clay/salt mixture, asphalt) are adapted to the surrounding geology and the chemical impact of circulating groundwater.																					
		2 Shaft lining	Describes the chemical, hydraulic, mechanical and thermal properties of the shaft lining that is restricted to the overburden formations and to the top of the host rock. Shaft lining is designed to function during operation period. After closure shaft lining will fail after a few decades.																					
		3 Shaft backfill	Describes the chemical, hydraulic, mechanical and thermal properties of the shaft backfill (gravel column) on top of the shaft seal. The Uppermost parts the shafts have to be backfilled in compliance with mining regulations.																					
		4 Concrete corrosion products	Describes the chemical, hydraulic, mechanical and thermal properties of the concrete corrosion products of the shaft seal, concrete lining, injections and borehole seals																					
		5 Metal corrosion products	Describes the chemical, hydraulic, mechanical and thermal properties of the metal corrosion products (e.g. steel shaft lining).																					
		6 Contact Zone	Describes the geometry and the hydraulic properties of the void volume between the barrier and the drift contour. May be sealed by concrete injections or by salt creeping (convergence)																					
		7 Excavation damaged zone in the overburden formations	Describes the chemical, hydraulic, mechanical and thermal properties of the EDZ at the time of repository closure. The properties and extent of EDZ depend on the rock properties and the stabilization measures (lining). Fissures of EDZ may be closed by convergence.																					
		8 Excavation damaged zone in host rock	Describes the chemical, hydraulic, mechanical and thermal pro-perties of the EDZ at the time of repository closure. The properties and extent of EDZ depend on the rock properties and the stabi-lization measures (lining). Fissures of EDZ may be closed by convergence.																					
		9 Liquids in shaft	This FEP describes the quantities and the chemical properties of the liquids (groundwater and hydrocarbons in the shaft column incl. EDZ/contact zone,																					
		10 Gases in shaft	This FEP describes the quantities and the chemical properties of free gases and gaseous hydrocarbons in the shaft and the EDZ/contact zone.																					

					Components affected by processes																			
Subsystem Shaft	**Process Group**	**FEP (No. referring to the components mentioned in right column)**	**Description**	**Direct impact of processes on barrier function and other shaft components**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		11 Concrete injections	Describes the chemical, hydraulic and mechanical properties of the injection material. Concrete injections may be used to seal contact zone, EDZ and fractures in surrounding rocks.																					
		12 Exploration and monitoring drillings	Describes the chemical, hydraulic, mechanical and thermal pro-perties of backfilled drillings arranged at the shaft contour to explore or monitor the surrounding host rock, overburden formations. The backfilling material is adapted to the surrounding geology and the chemical impact of circulating groundwater.																					
		13 Overburden formations	Describes the chemical, hydraulic, mechanical and thermal properties of the overburden formations at the time of repository closure																					
		14 Fractures and faults in the overburden Formations	Describes the chemical, hydraulic, mechanical and thermal properties of fractures and faults and their mineralization in the overburden formations at the time of repository closure																					
		15 Liquids in the overburden formations	This FEP describes the quantities and the chemical properties of the liquids in the overburden formations. The geological formations may include several aquifers with different hydrochemistry as well as hydrocarbon reservoirs.																					
		16 Gases in the overburden formations	This FEP describes the quantities and the chemical properties of the gases in the overburden formations. Most common gases are CO_2, N_2 and CH_4.																					
		17 Host rock	Describes the chemical, hydraulic, mechanical and thermal properties of the host rock at the time of repository closure.																					
		18 Fractures and faults in host rock	Describes the chemical, hydraulic, mechanical and thermal properties of fractures and faults and their mineralization in the hostrock at the time of repository closure																					
		19 Liquids in host rock	This FEP describes the quantities and the chemical properties of the liquids in the hostrock. Apart from very small fluid inclusions in salt and fractured anhydrite formations are potential reservoirs. Liquids in salt formations include brine (in equilibrium with surrounding salt) and hydrocarbons.																					
		20 Gases in host rock	This FEP describes the quantities and the chemical properties of the liquids in the hostrock. Apart from very small fluid inclusions in salt, fractured anhydrite formations are potential reservoirs. Common gases in salt formations include CO_2, N_2 and CH_4.																					
Processes/Events	**Mechanical**	**Earth quake**	The release of accumulated geologic stress via rapid relative movements within the Earth's crust usually along existing faults or geological interfaces. The accompanying release of energy may result in ground movement and/or rupture.	Earth quakes may particularly affect the shaft components shortly after repository closure. Then the shaft seal is not yet fixed in the shaft column.	✓	✓	✓	✓	✓		✓	✓			✓	✓	✓	✓			✓	✓		

					Components affected by processes																			
Subsystem Shaft	**Process Group**	**FEP (No. referring to the components mentioned in right column)**	**Description**	**Direct impact of processes on barrier function and other shaft components**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		Permafrost	Soil and uppermost part of the overburden rock formations that were permanently frozen during ice age.	X) will occur after the functional lifetime of the geotechnical barriers	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓			✓	✓	✓	
		Effects of glaciers and ice sheets	Include processes like exaration (a glacial erosion process). Glaciation will increase the mechanical load on the repository system.	X) will occur after the functional lifetime of the geotechnical barriers	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Glacial channelling	Below a glacier, melting water may erode glacial channels. May destroy uppermost parts of shaft and reduce mechanical load	X) will occur after the functional lifetime of the geotechnical barriers	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓						
		Diapirism	Uplift of thick salt formations due to density inversion, stresses resulting from overlying rock formations and tectonic structures.	X) The uplift of the salt dome may induce stresses in the shaft seal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Mechanical stress changes	Describes the transition of tension resulting from an increase or decrease of tension in the rocks or a component of the repository.	If stresses exceed material stability, they may result in fractures in the shaft seal and lining, the EDZ, the concrete injections, the borehole seals, the host rock and the overburden formations.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Swelling, shrinking and creeping of concrete	Describes not thermally induced volume or pressure changes of concrete.	They will modify the properties of shaft seal, shaft lining, injection material in contact zone / EDZ and borehole sealings.	✓	✓		✓					✓		✓	✓			✓				✓	
		Swelling and shrinking of bentonite	Means the adsorption and release of water from the crystal interim layer of clay minerals	Will modify the properties of the shaft seal and close the contact zone as well as the fissures in the EDZ	✓								✓						✓				✓	
		Settlement and compaction of backfill	Settlement means the slow lowering of non cohesive materials for backfilling and closure. This leads to compaction and hardening. Driving forces for this process are gravitation and the load of the surrounding geosphere.	Will modify the properties of crushed salt and the gravel column of the shaft seal.			✓	✓					✓						✓					
		Convergence	Describes rock creeping into the mine excavations. Creeping rates depend on the mechanical properties of the rocks: high in salt formations, low in brittle hard rocks (anhydrite).	Convergence will fix the shaft seal in the shaft column and close the contact zone as well as the fissures in the EDZ						✓	✓	✓					✓	✓			✓	✓		
		Displacement of shaft sealing element	Describes the displacement of sealing elements of the shafts from their installation position by mechanical or hydraulic impacts.	The displacement of sealing elements may result in flow paths at the shaft contour	✓					✓	✓	✓			✓									
	Hydraulic	**Transgression and regression**	Offshore or onshore relocation of the coast line (flooding and landing). May be influenced by man-made climate change	A flooding of the repository site would result in an increased hydraulic pressure at the shaft seal	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
		Surface water bodies	During future site evolution existing rivers, lakes etc. may be relocated and their extent/volume changed. Flooding of shafts has to be considered.	Little impact on geotechnical barriers	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
		Liquid flow processes	Describes the liquid flow because of potential gradients. They may modify the hydraulic properties of the shaft seal, injection material and borehole seals.	Liquid flow processes influence fluid pressure and may result in an erosion of construction materials and increase contact zone / EDZ	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Gas flow processes	Describes the gas flow because of potential gradients. Impact of high gas pressure is described in the FEP hydraulic pressure change.	Gas flow processes influence fluid pressure and thus impair geotechnical barriers	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Channeling in a sealing element	Generation of flow paths by inhomogeneous compaction or swelling or erosion of bentonite / concrete or viscous fingering in asphalt	Impairment of the function of the shaft sealing elements	✓			✓	✓				✓	✓		✓								
		Hydraulic pressure change	Describes a change of fluid pressure because of changes of tension in rocks or fluid flow processes.	High fluid pressure may induce fissures in barrier constructions and EDZ									✓	✓					✓	✓			✓	✓

					Components affected by processes																			
Subsystem Shaft	**Process Group**	**FEP (No. referring to the components mentioned in right column)**	**Description**	**Direct impact of processes on barrier function and other shaft components**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		Diffusion	Stirring of different substances by BROWN molecular movements.	The process is relevant for mass transport but will not directly affect the barrier function.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dispersion	Distribution of dissolved substances by inhomogeneous flow velocities in porous media.	The process is relevant for mass transport but will not directly affect the barrier function.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Liquid inflow	Describes the inflow of liquids from the host rock, the overburden formations via the EDZ into the mine openings.	Liquid inflow from geosphere will change hy-drochemistry and there-fore promote corrosion of construction materials	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓								
		Asphalt migration	Due to gravitation and/or hydraulic resp. mechanical loads asphalt can squeezed from shaft seals and migrate in the contact zone, the EDZ as well as pores, fractures and faults in the surrounding rock formations.	Asphalt migration results in a decrease of the asphalt volume in the shaft seal and thus impair the sealing function	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓	✓	✓				
		Phase transition	Describes the transition from solid to liquid or from liquid to gas depending from the composition of the material, the pressure and the temperature.	During the functional lifetime of the EBS no phase transitions will occur that can impair EBS function									✓	✓					✓	✓			✓	✓
		Dissolution and outgassing	Describes the transition of gas between gaseous phase and the dissolved phase.	The process is relevant for mass transport but will not directly affect the barrier function.									✓	✓					✓	✓			✓	✓
		Radionuclide transport in the liquid phase	Summarizes all kind of transport processes of radionuclides in liquids.	The process is relevant for release of radionuclides but will not directly affect the function of the barriers.	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	
		Radionuclide transport in the gas phase	Summarizes all kind of transport processes of radionuclides in gas.	The process is relevant for release of radionuclides but will not directly affect the function of the barriers.	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓		✓
	Thermal	Heat flow	Means the energy transport as a result of temperature differences. There are 3 sources for heat flow: climate, geothermy and radionuclide decay of the waste	Indirect impact, induces mechanical and chemical processes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Thermal expansion or contraction	Volume changes resulting from temperature change. In the shafts,. TM stresses are predominately climate induced. They are only relevant during glacial periods and then they may impair all constructions in the shafts, the EDZ and the rock formations.	X) During glacial periods, thermomechanical stressses may induce fis-sures in the components of the shaft seals. Thus the function of the seals may be impaired. Due to the distance to the disposal areas, the shafts will not be impaired by thermomechanical stresses resulting from heat generating waste.	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	
	Chemical / biological	**Concrete corrosion**	Describes the chemical degradation of concrete	The corrosion processes will impair the function of all concrete components in the shafts: shaft seal, shaft lining, borehole seals and injections. For sealing constructions the mechanical stability of abutments may be be reduced and the hydraulic conductivity of seals increased.	✓	✓		✓					✓		✓	✓			✓				✓	
		Solution and precipitation of salt minerals	Solution describes the transition of a solid phase (salt minerals) into the liquid phase due to a change of hydrochemical boundary conditions. Precipitation is the reverse process. This process is considered for crushed salt backfill and for EDZ.	This process will modify the hydraulic properties of salt backfill and the EDZ	✓		✓					✓	✓								✓	✓	✓	
		Metal corrosion	Describes the electrochemical reaction of metals with surrounding fluids and resulting gas generation. This process will reduce the mechanical stability of metal components.	Stabilization measures, like steel lining and roof bolts, will be impaired by corrosion. This may mo-dify the properties of the EDZ.	✓	✓			✓				✓	✓		✓			✓	✓			✓	✓
		Hydrogen embrittlement	The intrusion of hydrogen (from metal corrosion) in metal structures results in a modification of the mechanical properties.	In comparison to metal corrosion of low relevance	✓	✓								✓		✓				✓				✓

					Components affected by processes																			
Subsystem Shaft	**Process Group**	**FEP (No. referring to the components mentioned in right column)**	**Description**	**Direct impact of processes on barrier function and other shaft components**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		Microbial processes	Summarizes all microbial processes in the mine and in the surrounding rocks. Important for degradation of organics, but may also force the corrosion of metal and concrete.	May directly impair the function of the shaft seal and lining by degradation of asphalt and indirectly by intensifying corrosion processes	✓	✓		✓		✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	
		Chemical alteration of organica	Describes the alteration of organic matters in the shaft seal (asphalt, organic compounds in clay) and lining (asphalt filled joint) by chemical processes.	Lower relevance in comparison to microbial processes.	✓	✓							✓						✓		✓		✓	
		Alteration of bentonite	Describes the solution, transformation and regeneration of bentonite due to hydrochemical, biological and thermal environmental conditions. As a consequence the mineralogical and chemical properties of the bentonite have been changed.	Bentonite alteration may impair the sealing function of the bentonite seal.	✓								✓		✓				✓				✓	
		Sorption and desorption	Sorption describes the physico-chemical interaction of dissolved species with a solid phase. Desorption is the opposite effect.	The process is relevant for mass transport but will not directly affect the barrier function.																				
		Complexation	Describes the impact of complexing agents on the radioactive waste.	The process is relevant for mass transport but will not directly affect the barrier function.																				
		Colloid generation and filtration	Generation of colloids and their filtration during transport.	May have an impact on bentonite barriers.																				
	Radiological	Radiological decay and ionizing radiation	Spontaneous transformation of instable atomic nuclei combined with the emission of characteristic ionizing radiation.	The process is relevant for release of radionuclides but will not directly affect the function of the barriers.																				

7.3.2 Subsystem Nearfield of drift seal

The Subsystem nearfield of drift seal is part of the compartment “Shafts, infrastructures and connecting drifts” (see chap. 5.2). It includes part of a connecting drift (with EDZ), the drift lining, the construction materials (incl. corrosion products), the drift seal consisting of a sealing element, abutments and contact zone, the backfill, fluids and adjacent parts of the host rock, see Figure 7-2. The components of the near field are influenced by numerous mechanical, hydraulic, chemical and thermal processes initiated in the farfield. So mechanical loads not only result from lithostatic pressure but from modifications of geosphere stress field by tectonic movements (e.g. subsidence, uplift), earth quake or processes like glaciation, erosion and sedimentation. Hydraulic loads may results from brine inflow from anhydrite reservoirs and brine pockets in the salt formations as well as from liquids slowly percolating through the shaft seal and EDZ into the infrastructure area. Therefore a broad spectrum of hydraulic impacts is possible – so groundwater inflow the shaft as well as different brine types from salinar reservoirs with different hydrochemistry. The fluid pressure will depend on gas generation by metal corrosion on one hand and convergence of the underground excavations on the other hand. Due to the distance between the disposal areas and the drift seal sites there will be a moderate increase of temperature but significant thermal-mechanical stresses may occur. A compilation of all relevant FEP in the subsystem as well as their short description (components) resp. a characterization on the potential impact of processes on EBS and an itemization of affected components, is given in table 7-3. FEPs that are excluded in a screening process due to their low probability and/or intensity are not mentioned.

Table 7-3: FEP lists for the subsystem “Drift seal”. Processes that may directly affect the EBS function (Initial FEP) are red marked.

					Components affected by process														
Sub-system: Drift	**Process Group**	**FEP (No. referring to the components mentioned in right column)**	**Description**	**Direct impact of processes on barrier function and other mine components**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Components		1 Drift seal	Describes the chemical, hydraulic, mechanical and thermal properties of the drift seal at the time of repository closure. Drift seals consist of abutments and sealing elements. The construction materials (salt and magnesium concrete) are adapted to the surrounding salt rock and the hydrochemistry of possibly inflowing brine.																
		2 Drift lining	Describes the chemical, hydraulic, mechanical and thermal properties of the drift lining at the time of repository closure. Drift lining will be installed in mine excavations with a long operating time (e.g. infrastructure, access drifts) or salt formations with low mechanical stability (e.g. anhydrite). Drift lining is designed to function during operation period. After closure drift lining will fail after a few decades.																
		3 Drift backfill	Describes the chemical, hydraulic, mechanical and thermal properties of the drift backfill at the time of repository closure. Crushed salt and concrete are common backfill materials.																
		4 Concrete corrosion products	Describes the chemical, hydraulic, mechanical and thermal properties of the concrete corrosion products of the drift seals, concrete linings, injections and borehole seals.																
		5 Metal corrosion products	Describes the chemical, hydraulic, mechanical and thermal properties of the metal corrosion products (e.g. partition plates or reinforcement in concrete components, rock bolts).																
		6 Contact Zone	Describes the geometry and the hydraulic properties of the void volume between the barrier and the drift contour. May be sealed by concrete injections or by salt creeping (convergence)																
		7 Excavation damaged zone in host rock	Describes the chemical, hydraulic, mechanical and thermal properties of the EDZ at the time of repository closure. The properties and extent of the EDZ depend on the properties and the stabilization measures (lining). Fissures of EDZ may be closed by convergence.																
		8 Concrete Injections	Describes the chemical, hydraulic, mechanical and thermal properties of concrete injections that are provided to seal fractures and																
		8 Liquids in underground excavations	This FEP describes the quantities and the chemical properties of the liquids (brine and hydrocarbons in the drift incl. EDZ/contact zone,																
		9 Gases in underground excavations	This FEP describes the quantities and the chemical properties of free gases and gaseous hydrocarbons in the drift and the EDZ/contact zone.																
		10 Concrete injections	Describes the chemical, hydraulic and mechanical properties of the injection material. Concrete injections may be used to seal contact zone, EDZ and fractures in the surrounding rocks.																

					Components affected by process														
Sub-system: Drift	**Process Group**	**FEP (No. referring to the components mentioned in right column)**	**Description**	**Direct impact of processes on barrier function and other mine components**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		11 Exploration and monitoring drillings	Describes the chemical, hydraulic, mechanical and thermal properties of sealed drillings arranged at the drift contour to explore or monitor the surrounding host rock. The backfilling material is adapted to the surrounding geology and the chemical impact of circulating groundwater.																
		12 Host rock	Describes the chemical, hydraulic, mechanical and thermal properties of the host rock at the time of repository closure.																
		13 Fractures and faults in host rock	Describes the chemical, hydraulic, mechanical and thermal properties of fractures and faults and their mineralization in the host rock at the time of repository closure																
		14 Liquids in host rock	This FEP describes the quantities and the chemical properties of the liquids in the host rock. Apart from very small fluid inclusions in salt, fractured anhydrite formations may include fluid reservoirs (brine and hydrocarbons). Brines in salt formations are in equilibrium with surrounding salt.																
		15 Gases in host rock	This FEP describes the quantities and the chemical properties of the liquids in the host rock. Apart from very small fluid inclusions in salt, fractured anhydrite formations are potential reservoirs. Common gases in salt formations include CO2, N2 and CH4.																
Processes / Events	**Mechanical**	**Earth quake**	The release of accumulated geologic stress via rapid relative movements within the earth's crust will occur along existing faults or geological interfaces. The accompanying release of energy may result in ground movements and/or ruptures.	Earth quakes may particularly affect the drift components shortly after repository closure. Then the drift seal and the backfill are not yet fixed in the drift cross section. Later, seismic movements may yield in fractures in the drift seal. The drift lining may collapse.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Diapirism	Uplift of thick salt formations due to density inversion, stresses resulting from overlying rock formations and tectonic structures.	X) The uplift of a salt dome may induce stresses in a drift seal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Mechanical stress changes	Describes the transition of tension resulting from an increase or decrease of tension in the rocks or a component of the repository.	If the stresses are exceeding material stability, they may result in fractures in the drift seal and lining, the EDZ, the concrete injections, the borehole seals, and the host rock.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Swelling, shrinking and creeping of concrete	Describes not thermally induced volume or pressure changes of concrete in the drift seal, drift lining, backfill, injections and borehole seals.	This process will modify the properties of all concrete components and close the contact zone as well as the fissures in the EDZ.	✓	✓	✓	✓						✓	✓				
		Settlement and compaction of backfill and sealing materials	Settlement means the slow lowering of non-cohesive backfill materials (e.g. crushed salt) and to a minor extent construction materials like concrete. This leads to compaction and hardening. Driving forces for these processes are gravitation and convergence.	As a consequence, the hydraulic conductivity will decrease and the mechanical stability of the materials will increase.	✓	✓									✓				
		Convergence	Describes rock creeping into the mine excavations. Creeping rates depend on the mechanical properties of the rocks: high creeping in salt formations, low creeping in brittle hard rocks (anhydrite).	Convergence will fix the drift seal in the drift cross section and close the contact zone as well as the fissures of the EDZ	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Hydraulic	**Liquid flow processes**	Describes the liquid flow due to potential gradients. Flow processes result in mass transport on one hand and may modify the hydraulic properties of the drift seal, injection material and borehole seals on the other hand.	Liquid flow transport is important for chemical processes and radionuclide spreading. Furthermore fluid flow may result in an erosion of construction materials and enlarge contact zone and/or EDZ								✓						✓	
		Gas flow processes	Describes the gas flow due to potential gradients. Gas flow is responsible for transport of volatile compounds. Impact of high gas pressure is described in the FEP hydraulic pressure change.	Gas flow transport is important for chemical processes and radionuclide spreading. Furthermore fluid pressure may impair geotechnical barriers									✓						✓

					Components affected by process														
Sub-system: Drift	**Process Group**	**FEP (No. referring to the components mentioned in right column)**	**Description**	**Direct impact of processes on barrier function and other mine components**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Channeling in a sealing element	Generation of flow paths by varying concrete properties, inhomogeneous compaction or swelling or erosion of bentonite or viscous fingering in asphalt	Impairment of the function of the drift / borehole sealing elements	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Backfill channeling	Generation of flow paths by varying concrete properties or settlement of crushed salt and inhomogeneous compaction. Due to compaction gradients, the flow paths occur predominately at the drift roof.	The sealing and stabilizing function of the backfill will be retarded.		✓													
		Hydraulic pressure change	Describes a change of fluid pressure because of changes of tension in rocks or fluid flow processes.	High fluid pressure may induce fissures in barrier constructions and EDZ	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Diffusion	Stirring of different substances by BROWN molecular movements. Diffusion is only considered in liquids and gases and will reduce concentration gradients in those fluids. Therefore it will also influence hydrochemistry.	The process will indirectly (via hydrochemistry) influence corrosion processes at the drift and borehole seals.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dispersion	Distribution of dissolved substances by inhomogeneous flow velocities in porous media. The process is linked to advective or convective mass transport and will influence hydrochemistry.	The process will indirectly (via hydrochemistry) influence corrosion processes at the drift and borehole seals.	✓		✓	✓		✓	✓	✓			✓		✓	✓	
		Liquid influx	Describes the influx of liquids from the host rock into the mine openings.	Liquid influx from geosphere will change hydrochemistry in mine and therefore indirectly promote corrosion of construction materials								✓						✓	
		Phase transition	Describes the transition from solid to liquid or from liquid to gas depending from the composition of the material, the pressure and the temperature. In mine openings evaporation and condensation are processes that will influence the distribution of humidity in the mine openings.	No relevant impact on the EBS								✓	✓						
		Dissolution and outgassing	Describes the transition of gas between gaseous phase and the dissolved phase.	The process is relevant for mass transport but will not directly affect the barrier or components functions.								✓	✓					✓	✓
		Fluid pressure induced permeation of gas into salt formations	If fluid pressure exceeds the minimum main stress in the host rock, the permeability of the salt formations will be increased and fluids can infiltrate the effected formations.	Gas permeation in salt formations may bypass the drift seals							✓	✓	✓			✓	✓	✓	✓
		Radionuclide transport in the liquid phase	Summarizes all kind of transport processes of radionuclides in liquids.	The process is relevant for release of radionuclides but will not directly affect the function of the barriers.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Radionuclide transport in the gas phase	Summarizes all kind of transport processes of radionuclides in gas.	The process is relevant for release of radionuclides but will not directly affect the function of the barriers or other mine components.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Thermal	Heat flow	Means the energy transport as a result of temperature differences. There are 2 main sources for heat flow in the drift: geothermic and radionuclide decay of the waste. Due to the depth of repository level climate impact is of low relevance. Temperature is a key issue of all chemical processes and temperature gradients may result in convective fluid flow.	Due to the distance between the barriers and the emplacement fields temperature limits for concrete and bentonite stability will to be met. Therefore temperature will not directly result in an impairment of the barriers.	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
		Thermal expansion or contraction	Volume change resulting from temperature change. At the emplacement level heat generating from waste disposal is of highest relevance. Depending on mine depth, cooling during future glacial periods may influence the emplacement level to a low intensity.	Thermomechanical stresses due to waste disposal may induce fissures in the components of the drifts.	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓

					Components affected by process														
Sub-system: Drift	**Process Group**	**FEP (No. referring to the components mentioned in right column)**	**Description**	**Direct impact of processes on barrier function and other mine components**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Thermochemical sulfate reduction	Redox reaction of organic matter or hydrogen with sulphate at high temperatures (starting temperature 80 °C) Resulting products are carbonate, sulphide, water, hydrogen sulphide, or carbon dioxide. The volume of the products is 10 % larger than the volume of the educts. Therefore mechanical stresses will occur.	At adequate boundary conditions the process may not impair EBS	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓		✓	✓
		Thermal degradation of carnallite	The mineral carnalite is characterized by 40 weight % of crystal water that is released at different hydration levels with increasing temperature (starting temperature 80 °C)	The water from degradation of carnallite at the site of a drift seal may contribute to the alteration of construction material. Furthermore the alteration of carnallite may result in the generation of flow paths that are bypassing the drift seal.							✓					✓	✓		
		Evaporation and condensation of water	Evaporation describes the phase transition from liquid to gas phase. Condensation is the reverse process.	No relevant impact on EBS	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Chemical / biological	**Concrete corrosion**	Describes the chemical degradation of concrete	The corrosion processes will impair the function of all concrete components in the drifts: drift seal, drift lining, borehole seals and injections. For sealing constructions the mechanical stability may be reduced and the hydraulic conductivity increased.	✓	✓	✓	✓				✓		✓	✓				
		Solution and precipitation of salt minerals	Solution describes the transition of a solid phase (salt minerals) into the liquid phase due to a change of hydrochemical boundary conditions. Precipitation is the reverse process. This process is considered for crushed salt backfill and for EDZ.	This process may modify the hydraulic properties of salt backfill and the EDZ			✓			✓	✓	✓				✓	✓	✓	
		Transformation of anhydrite to gypsum	Calcium sulphate reacts with water to generate gypsum. This exothermal reaction results in an increase of volume of 61 %. As a consequence swelling pressures of up to 4,5 MPa may occur.	This process may especially modify the hydraulic properties of the EDZ.							✓	✓				✓		✓	
		Metal corrosion	Describes the electrochemical reaction of metals with surrounding fluids and resulting gas generation. This process will reduce the mechanical stability of metal components. The enlargement of volume (factor 3.6) of the metal corrosion products will result in significant stresses in the concrete constructions.	Stabilization measures, like steel lining and roof bolts, will be impaired by corrosion. This may impair the EDZ. If the drift seal includes metal components (e.g. partition plates or reinforcements in concrete) the corrosion could also affect the sealing function.	✓	✓			✓						✓				
		Hydrogen embrittlement	The intrusion of hydrogen in metal structures results in a modification of the mechanical properties.	Low relevance for EBS alteration	✓	✓			✓						✓				
		Deflagration and explosion of gases	A deflagration or explosion resulting from the ignition of a flammable gas mixture in the repository	An explosion may have impact on the integrity of the drift seal									✓						✓
		Microbial processes	Summarizes all microbial processes in the mine and in the surrounding rocks. Microbial processes may force the corrosion of metal and concrete.	May impair the function of the drift seal, backfill and lining	✓	✓	✓					✓	✓						
		Sorption and desorption	Sorption describes the physico-chemical interaction of dissolved species with a solid phase. Desorption is the opposite effect.	The process is relevant for mass transport but will not directly affect the barriers or other components.						✓		✓	✓					✓	✓
		Colloid generation and filtration	Generation of colloids and their filtration during transport.	The process is relevant for mass transport but will not directly affect the barriers or other components.						✓		✓	✓					✓	✓
	Radiological	Radiological decay and ionizing radiation	Spontaneous transformation of instable atomic nuclei combined with the emission of characteristic ionizing radiation. After the release of radionuclides in the emplacement areas, they will be spread in the mine excavations and radiological decay will occur during transport.	The heat generation from radiological decay is a relevant thermal input in the repository system. It will result in thermomechanical stresses and influence the chemical processes. Thus all components are affected.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

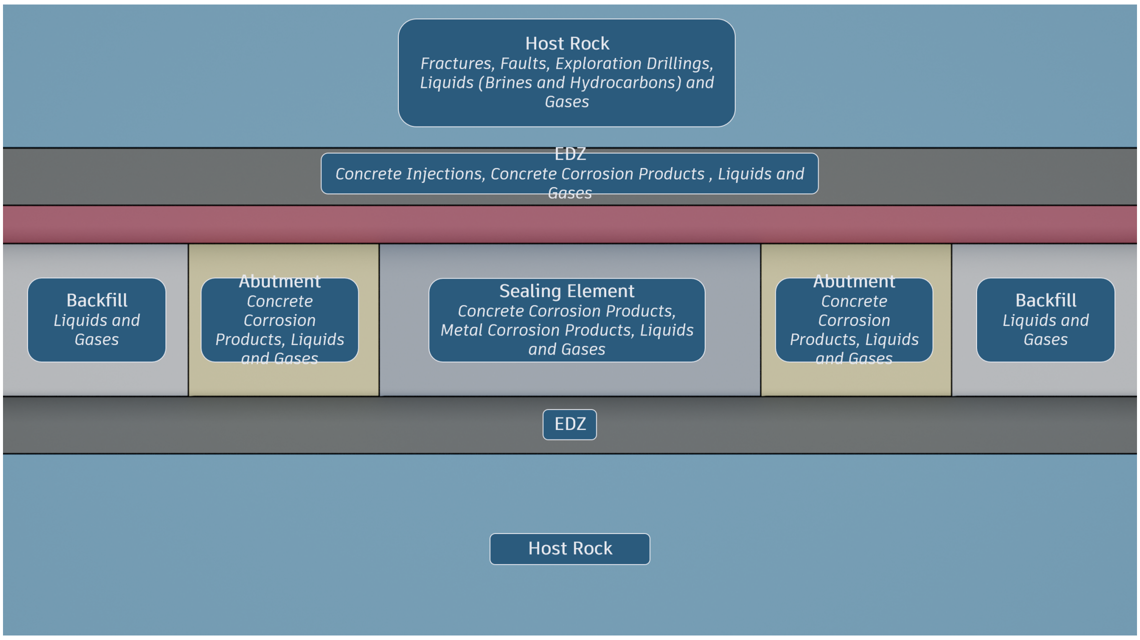

Figure 7-2: Nearfield model for the drift seal, FEPs in italics

FEP of the farfield that have a direct impact on the subsystem drift seal are compiled in the FEP list of compartment "shafts, infrastructure and connecting drifts" in table 7-1.

7.4 Methodology of Scenario Development

The fundamentals of scenario development were comprehensively described in Beuth et al. (2012) and Lommerzheim et al. (2019). Therefore, only a short summary will be given here.

7.4.1 Fundamentals

The site and the repository system will undergo a specific evolution, which will be controlled both by climatic and geologic processes at the site and processes induced by the repository construction and the emplacement of heat-generating waste. Although the various influencing factors are widely understood, this real evolution cannot be predicted unequivocally in all detail.

Developing and investigating several scenarios is an internationally recognized and accepted approach to address this uncertainty (NEA, 2016). In accordance with the Safety Requirements (BMU, 2010), different kinds of scenarios have to be considered as a basis for the safety assessment of a repository system. Expected, alternative, hypothetical and human intrusion scenarios reflect the variations of possible future site evolutions (Figure 7-4).

“Expected scenario” refers to a normal evolution forecast for the site, and evolutions normally observed at comparable locations or similar geologic situations (= Reference scenario).

“Alternative scenarios” refer to evolutions that are not expected for the site, but which may occur with regard to geological or climatic boundary conditions, the technical and geotechnical barriers and the radioactive inventory.

Expected and alternative scenarios will be systematically derived from the FEP catalog.

Other groups of scenarios include “hypothetical scenarios” and “human intrusion scenarios”. Those scenarios will be analyzed with regard to an optimization of the repository system and to assess the robustness of the system.

“Hypothetical scenarios” include evolutions that can be excluded even for most unfavorable assumptions basing on expert judgment. These scenarios include “what-if-cases”.

“Human intrusion scenarios” reflect consequences resulting from future human actions, esp. unintended human intrusion in the repository, that are relevant for the safety of the repository system. Reference scenarios for those evolutions can be derived from common recent human activities (Figure 7-4). The basic conditions for consideration of those impacts are also defined in BMU (2010) and EndlSiAnfV (2020).

Hypothetical and human intrusion scenarios are not included in the RANGERS project.

Conceptions concerning the future evolution of a repository system are prerequisites for numerical long-term safety assessments. Therefore, the scenario development methodology aims at systematically deriving expected reference scenarios and a number of alternative scenarios that are to comprehensively represent the reasonable range of repository system evolutions (Beuth et al., 2012; Lommerzheim et al., 2019). The scenarios are characterized by FEP that will influence the future evolution of the final repository system at the reference site and their associated characteristics. An overview of the scenario development methodology is given in Figure 7-3.

In the scenarios, possible future evolutions of the repository system during the safety demonstration period are described comprehensively. The methodology applied relies on several fundamentals, i.e. the regulatory framework, the safety concept, basic assumptions, the geologic data, the waste data and the repository concept, and integrates all data relevant to scenario development into the FEP catalog.

There are three key issues that rely directly on the guiding principles of the safety concept to start scenario development:

- “Initial barriers” are important components of the safety concept and are characterized by the safety functions “restriction of advective and diffusive mass transport” as well as “retardation of radionuclides”. They have defined properties just after repository closure and will be modified in different time frames.
- “Initial FEP” are expected processes that could impair the safety functions of the initial barriers. They provide the first starting points for scenario development.
- In addition, all possible system evolutions that involve a release of radionuclides from the waste form need to be considered. Those FEP, that are related to the mobilization of radionuclides and their transport, are additional starting points for scenario development.

A plausibility check has shown that the initial FEP consider all relevant impacts on the geological and geotechnical barriers. Therefore they are adequate starting points for scenario

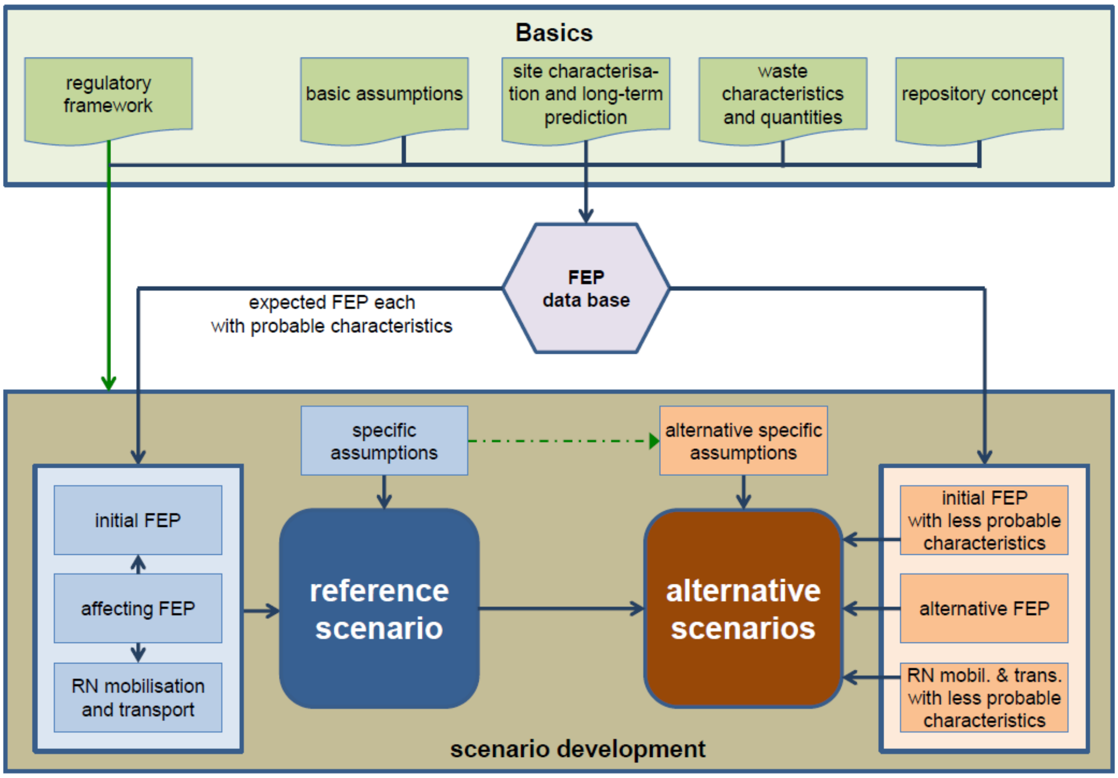

Figure 7-3: Scenario development methodology (modified after Mönig et al. 2013)

development.

The description of FEP interaction by component-process-causal chains results in long, but clear causal chains to address important aspects of system evolution. To facilitate the generation of adequate dependence trees, a tool with break-off criteria can be applied.

7.4.2 Reference scenario

A (expected) reference scenario does not include one specific evolution but describes as broadly as possible the spectrum of probable future evolutions of a repository system.

The “initial barriers” considered in salt formations include the host rock, the shaft, borehole and drift seals as well as the backfill.

The processes that may directly affect the safety functions of the initial barriers are called initial FEP. They are marked in the FEP-Lists of tables 7-1, 7-2 and 7-3.

The starting points for developing reference scenarios are:

1. specific assumptions: provide a means to deal in a transparent and traceable way with particular uncertainties, some of which may be minimized in the future while others may never be reduced at all. They especially address three aspects with high uncertainty and assume for the reference scenario:

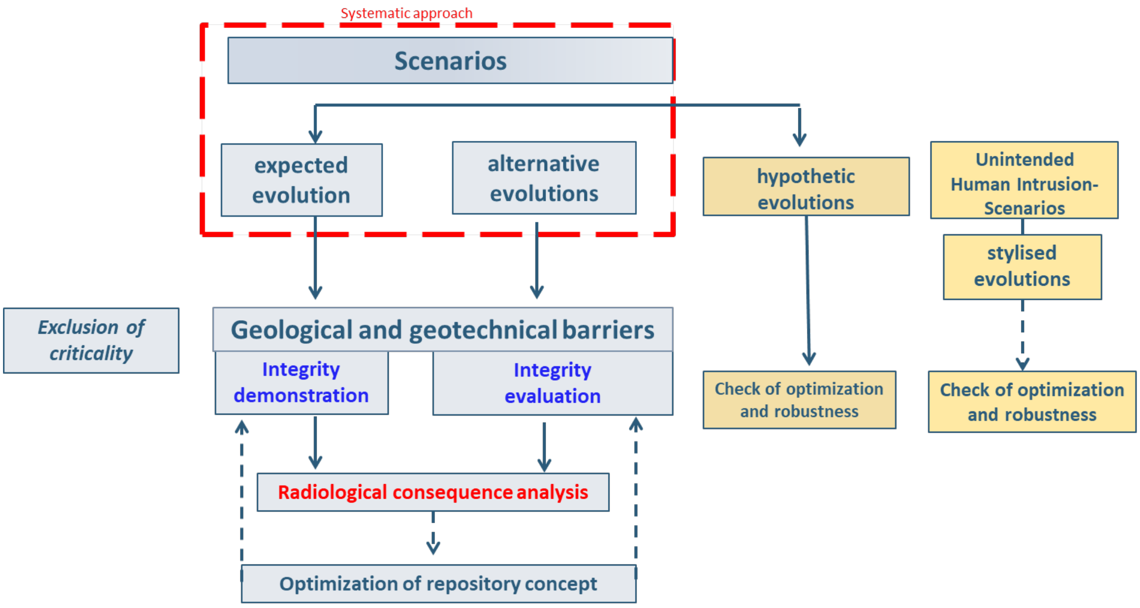

Figure 7-4: Classification of scenarios and safety demonstration methodology

- Geology: the available geological data are representative and there are no undetected geological characteristics. The uncertainty in this point can only be reduced by future exploration .
- Safety function of technical/geotechnical barriers: All technical/geotechnical barriers work as designed. The functionality of the engineered barriers has to be verified by an integrity proof.
- Future climate evolution: Because of the persisting uncertainties in this issue all reasonable climatic evolutions have to be considered as “expected”. The evolution with the highest plausibility will be attributed to the reference scenario. Other probable climate evolutions will be analyzed as probable alternative scenarios.

2. The expected initial FEP with their probable characteristics: If appropriate information is available in the FEP catalog, the representative characteristics of those initial FEP have been taken for scenario description. Otherwise, the characteristics of the initial FEP have to be derived from their interaction with other FEP (causal chains) in combination with orienting process modeling.

3. Expected FEP characterizing the mobilization and transport of radionuclides with probable characteristics: The characteristics will be derived as described above.

Because the reference scenario results from the interaction between expected FEP, it will be expected as well.

The relevant process FEP may have different characteristics at different times and at different locations of the repository system. Therefore, it is useful to subdivide the description of the reference scenario into subsystems like near field, remaining mine excavations, host rock, and overburden to optimize the clarity and traceability of the description and to consider the interrelation between the subsystems and possible chronological limits of the initial FEP.

Due to the numerous starting points of scenarios development, the methodological approach is a “bottom-up”-type: The description starts on a broad basis and then comes to a comprehensive description of the repository system.

7.4.3 Alternative Scenarios

Alternative scenarios are evolutions that differ in exactly one aspect from the reference scenario (top down approach). The consequences on repository system evolution can be identified by an analysis of the differences to the reference scenario. Alternative scenarios can be developed from the following starting points (Figure 7-4):

- deviations concerning the specific assumptions: This approach may yield alternative scenarios and expected scenarios – not yet covered by the reference scenario. Examples for deviations from specific assumptions, that may result in alternative scenarios, are:
  - Undetected geological properties (e.g. fracture zones or fluid reservoirs),
  - Early failure of shaft seal (or drift seal, borehole seal, etc.),
  - Modifications of the future climate evolutions, e.g. changed characteristics of glacial periods (thickness of glaciers, depth of permafrost, dimensions of glacial channels, modified duration of glacial cycles)
- Less probable characteristics of the initial FEP: for the initial FEP (see Figure 7-4), less probable characteristics have to be defined, and the consequences on repository system analysis have to be evaluated. If a significant impact would be expected and the consequences are not yet covered by any other alternative scenario, a new alternative scenario has to be proposed. For example, for the process FEP “metal corrosion”, a corrosion rate twice as high as for normal evolution would be a less probable characteristic. Metal corrosion is a key issue for gas generation and radionuclide mobilization. Therefore this process is not only relevant with regard to the function of the disposal canisters. The consequences of a high corrosion rate are not covered by the “early failure of a disposal canister” but an additional alternative scenario with a high gas pressure is necessary.
- Less probable characteristics of the process FEP mobilization and transport of radionuclides: for the procedure to identify less probable characteristics of these processes see above. For example, for the less probable characteristics of radionuclide transport, flow processes and the hydraulic properties of the materials in the repository system and the host rock have to be considered. So, for the less probable radionuclide transport by diffusion, less probable diffusion coefficients for the materials and the host rock have to be evaluated. An adequate alternative scenario has to be defined.
- alternative FEP: process FEP describing modifications of technical features (e.g. Channeling in sealing elements and Flow paths in exploration drillings) may have a lower probability due to the comprehensive quality assurance measures for the preparation of construction materials and the performance of construction work. Therefore those FEP may be starting points for alternative scenarios.

It is possible that similar alternative evolutions result from different starting points. In this case, various evolutions may be abstracted into one representative alternative scenario that covers the characteristics of the various evolutions.

7.5 Characterization of reference scenario

As mentioned above, the German reference scenario, that has been developed for the Preliminary safety assessment of the Gorleben site (VSG) (Beuth et al., 2012) , has been taken as an example and slightly modified to be compatible with the German concept for a salt pillow (KOSINA project). The reference scenario is characterized by the following properties and evolutions:

Specific assumptions for the reference scenario include:

- The reference climate development with a 100.000 a-cycle of glacial and warm periods is representative. During future occurence of Elster like glaciations the formation of a deep glacial channel is considered.
- Shaft and drift seals will be constructed and function as required.
- There are no misinterpreted exploration results or unknown geological properties, that result in a decrease of the safety distance between mine excavations and brine bearing formations/drillings.

The objective of the geoscientific long term prognosis is to give a forecast of future evolution of geosphere resp. of processes that may have an impact on geosphere evolution (without repository impact). Many potential future evolutions can be excluded for a repository site because the site selection has to consider the site selection criteria defined in German Site Selection Act (StandAG, 2023). The geoscientific long term prognosis is based on the actualism principle. Most evolutions of geosphere and climate are very slow and long ranging processes that started millions of years in past and will therefore also persist in future. Hence the regional evolution in past was analyzed and basing on those results the future evolutions will be predicted. As a result, for the German regions with flat-bedded salt formations, slow tectonic movements (subsidence of 0.01 mm/a), no formation of new deep fracture zones, seismicity with a design earth quake of 7.0 MSK scale and only minimal salt diapirism (0.02 mm/a) have to be expected.

For Germany, a prognosis for future climate development during the demonstration period of 1 million years (ten cycles each with 100,000 years) has been given in Beuth et al. (2012). The German flat lying salt formations occur in regions which were covered by glaciers and ice sheets with a thickness of up to 400 m in the past. Therefore the resulting mechanical load on the emplacement level will be limited. Permafrost will reach a depth of up to 300 m, periglacial channels will cut into geosphere up a depth of 200 m. Therefore those climate induced impacts will not impair the function of the CRZ.

Climate development will result in complex consequences on geosphere evolution, e.g. by modifications of hydrochemistry and geosphere stresses. Intensity of erosion will depend on topography, geological properties, vegetation and climate (precipitation) and will have a higher intensity during ice ages and a lower intensity during warmer climates (average: 0.01 to 0.02 mm/a). Subrosion rate will be low as well (<0.1 mm/a). Summarizing the impacts from surface, none of those impacts will result in a significant impairment of the CRZ or the geotechnical barriers at the emplacement level.

As mentioned above, changes of the hydrochemistry are expected for the glacial period, but the precise hydrochemical characteristics are not predictable. Therefore an adequate design of the barriers (EBS) can not be defined. Hence for the glacial periods no integrity proof can be given. As a consequence the functional life time of the EBS is restricted to the period before the next glacial period (with well defined boundary conditions) – which means in Germany a period of 50,000 years. Therefore the main focus of scenario description for the RANGERS project is set on the pre-glacial period.

Important boundary conditions (geology, repository concept and sealing concept) for the reference scenario are described in chapters 4, 5 and 6. For the reference scenario the expected future evolution of the repository system will be described taking the initial FEP as well as process FEP describing radionuclide mobilization and transport as starting points. They are red and green marked in the FEP tables 7-2 and 7-3. For detailed description of the scenario and a comprehensive analysis of the FEP interactions see Beuth et al. (2012). In the following text, a short compilation of the most important characteristics of the repository system evolution in the different compartments is given:

7.5.1 Geosphere

The reference geosphere of the repository system is characterized by a salt pillow consisting of Zechstein formations with a maximum thickness of 800 m. In the geological model the overburden formations (Triassic, Tertiary and Quaternary rocks) have a thickness of 140 – 800 m. The most important Zechstein formation (and the Containment Providing Rock Zone = CRZ) is the Staßfurt main halite, which is the host rock for the disposal areas and has a maximum thickness of 600 m. The halite may have a humidity of up to 5 vol %. The minimum thickness of overlying rock formations is 400 m. The competent layers of the Main Anhydrite with fluid reservoirs are fragmented by salt movements and arching. Due to a salt barrier of 350 m on average between the emplacement level and the anhydrite, a possible linkage between the reservoirs and the underground excavations is only given in the shafts. The disposal of heat generating waste results in thermal-mechanical stresses and an uplift at the top of the structure for some meters. Furthermore fractures in the host rock will be induced.

The moderate design earth quake (Intensity 7) may reactivate fractures and faults especially at the boundary between different types of rock, but large scale fractures are not expected. It has to been analyzed whether new fractures in the host rock may become flow path between fluid reservoirs and the underground excavations.

During the glacial periods the overburden formations may be partly eroded especially by glacial channels. But the CRZ will not be impaired. Permafrost may significantly modify the hydrology and hydrogeology in the overburden. Furthermore, the glacial cooling will induce thermal-mechanical stresses in the top of the salt pillow.

7.5.2 Disposal areas

The disposal areas will be situated in the Main Halite Formation. For the halite a brine content of 1-5 vol. % has been assumed. A safety distance between disposal fields and the carnallitite formations will avoid thermal degradation of carnallite and crystal water release. The repository design is adapted to comply with thermal and thermal-mechanical requirements as well as to keep safety distances to the potash seam. The disposal drifts are backfilled with crushed salt.

The temperature maximum of the waste packages will be ca. 200℃ after 80-100 years. After disposal, temperature will rapidly decline. After few thousand of years, the temperature maximum will decline to the original geothermal level. The heat generation will significantly increase convergence rates in the nearfield and therefore force compaction of the crushed salt. This process is important for the enclosure of the waste packages.The heating will result in thermal-mechanical stresses in the containers, the backfill, the EDZ and the surrounding host rock. The disposal casks will be designed to resist all thermal, mechanical, hydraulic and chemical impacts during a period of 500 years after closure (which is the period of recovery as defined in the regulations).

Brine inflow in the disposal drifts will be intensified by thermomigration and thus intensify metal corrosion and resulting gas generation. As a consequence fluid pressure will be enlarged. A high pore pressure will retard the compaction of the backfill. Thermochemical sulfate reduction will modify hydrochemistry in the nearfield and will also intensify container corrosion. With regard to the containment function of the technical barriers a small amount of containers with undetected failures are considered. For those containers radionuclides mobilization and transport will start shortly after closure of the repository.

7.5.3 Shafts and drifts

This compartment includes all underground excavations except the disposal areas – namely the shafts, the infrastructure area and the drifts. Also the two subsystems “nearfield of shaft seal” and “nearfield of drift seal” are located in this compartment. The closure concept for those parts of the repository comprises shaft and drift seals and a backfill of the drifts with crushed salt as well as borehole seals for the exploration drillings. The drift seals separate the access drifts to the disposal areas from the infrastructure area. After EBS construction their tight fixation in the shaft/drift contour and thereby their functionality will be accomplished by the swelling of the construction material as well as by the convergence of the surrounding rocks. The EDZ will be recut before installation of the engineered barriers. Remaining fractures will be sealed by concrete injections. The fissures in the EDZ will be closed by convergence in several 100 years.

Due to the uncertainties for the prognosis of the boundary conditions during future glacial periods, the functional period of shaft and drift seals is restricted to 50,000 years. The subsequent long term sealing of the underground excavations will be ensured by the compacted backfill (crushed salt).

The infrastructure area will be backfilled with basalt gravel and will function as a fluid reservoir. The corresponding fluids will comprise groundwater flowing in via the shaft seals/EDZ, on one hand, and limited brine volumes from reservoirs in the anhydrite as well as from brine pockets in the rock salt, on the other hand. Additionally, mine air and gas from metal corrosion or microbial processes may significantly contribute to the fluid pressure in the mine excavations. The objective of the fluid reservoir is to avoid high hydraulic loads on the shaft and drift seals prior to their fixation in the excavations contour.

All excavations are backfilled with crushed salt. The initial roof cleavage will be closed by convergence in some decades of years. Subsequently the crushed salt will be compacted in a few thousand years by convergence. Then the backfill has similar mechanical and hydraulic properties than the surrounding rock and act as a long-term barrier.

7.5.4 Nearfield of Shaft Seal

The nearfield of the shaft seal comprises the shaft installations and the shaft seal incl. the EDZ from the surface up to the shaft landing as well as adjacent parts of the host rock and the overburden formations. Those components are influenced by broad spectrum of mechanical, hydraulic, chemical and thermal processes initiated in the farfield.

So mechanical loads not only result from lithostatic pressure but from modifications of geosphere stress field by geological processes (e.g. diapirism, tectonic movements), earth quake or processes like glaciation, erosion and sedimentation. Most relevant impacts are the earth quake (may induce fissures in concrete and settle and compact the gravel abutment) as well as the diapirism (induces stresses in the barrier). The estimated intensities of those processes/events have to be considered in the design of the construction. Other processes resulting in mechanical stress changes were initiated by volume changes of construction materials (e.g. swelling, shrinking and creeping of concrete and bentonite as well as settlement and compaction of backfill). Those processes may result in small displacements of the components of the shaft seal. Convergence is a very important mechanical process ensuring the fixation and functionality of the shaft seal. Reference values for convergence will be taken from experience in other salt mines.

Because this subsystem cuts through the whole geological sequence, not only the host rock but also the aquifers in the overburden formations and the underground facilities have to be considered. Therefore a broad spectrum of hydraulic impacts is possible – from the overburden, from anhydrite reservoirs and from brine pockets in the salt formations as well as (at late times) from fluids that are squeezed out from the underground excavation via the infrastructure area to the shafts. In the repository system a two phase flow of liquid and gas is often expected. The most important hydraulic process is the fluid pressure change that is mostly linked to fluid flow processes. Those processes may impair the EBS function by channeling in the bentonite or concrete seals or by "viscous fingering" resp. asphalt migration from the asphalt seals. Fluid squeezing by convergence and gas generation are the most important processes to initiate fluid flow and to change fluid pressure. Advection, dispersion and diffusion are important processes for radionuclide transport.

At the shaft seal, a broad spectrum of liquids with different hydrochemical properties have to be considered, e.g. unsaturated groundwater from the surface and the overburden formations and different kinds of brine (Na, K, Mg / Cl, SO_4 concentrations) from divers salt formations. Although different reference liquids are considered in barrier design by adequate construction materials, corrosion and alteration processes (e.g., concrete corrosion, alteration of bentonite, microbial processes) can not be excluded during the future site evolution. This is caused by uncertainties in the prognosis of the hydrological-chemical evolution.

At early times, the corrosion of the shaft liner determines the time of water inflow from adjacent aquifers and for the corresponding hydraulic loads at the shaft seal.

The thermal boundary conditions in the shafts are dominated by the (constant) geothermal heat flow as well as by climate induced heat flow (most relevant during glacial periods). The heat flow from the disposal of high level radioactive waste is of lower relevance due to the large distance between the disposal areas and the shafts. Nevertheless, the high heat input in the disposal fields will induce significant thermal-mechanical stresses (compressive strength) at the shafts. The climate induced cooling may result in tensile stresses and the generation of fractures at the top of the salt structure. With regard to the performance assessment of the geotechnical barriers that is of lower relevance because the functional time of the barriers is restricted to the pre-glacial period.

7.5.5 Nearfield of drift seal

The repository layout provides two disposal areas each connected with the infrastructure area and the shafts by four access drifts. Each drift has to be sealed by a drift seal to avoid a water inflow from the infrastructure area to the disposal areas or a release of possibly contaminated fluids from the disposal areas. The nearfield of the drift seal comprises the drift lining, the drift seal incl. the EDZ as well as adjacent parts of the host rock (see Figure 7-2). Those components are influenced by a broad spectrum of mechanical, hydraulic, chemical and thermal processes initiated in the farfield.

Modifications of the host rock stress field by geological processes (e.g. diapirism, tectonic movements), earth quake or processes like glaciation, erosion and sedimentation are also relevant at the emplacement level. Mining experience shows that the impact of seismic waves on the restrained geosphere decreases with increasing depth. But open parts of the mine excavations (e.g. top clefts above the backfill), the rigid concrete as well as the EDZ may be affected. If diapirism proceeds irregularly, stresses may be induced in the large drift seals. Other processes resulting in mechanical stress changes were initiated by volume changes of construction materials (e.g. swelling, shrinking and creeping of concrete). Convergence is a very important mechanical process ensuring the fixation and functionality of the drift seal. The reference convergence rate will be estimated from the experience in other salt mines.

Hydraulic conditions in the nearfield of the drift seal will be influenced by liquids in the infrastructure area. They will arise from surface or overburden formations by percolating through the shaft seal and the EDZ or from fluid reservoirs in the salt formations. Therefore the hydrochemistry of the liquids in infrastructure area may be quite inhomogeneous.

At the disposal area side of the drift seals only small amounts of brine solution from the host rock (brine pockets) will occur. But there are large amounts of metals (waste packages) in the disposals areas and their corrosion will result in an intensive gas generation, that will significantly increase fluid pressure at this side. If the leakage rate of drift seal is smaller than the gas generation rate, the fluid pressure will exceed the minimum stress in the host rock and fluid percolation in salt formations will start.

An asymmetrical fluid pressure is expected at the both sides of the drift seal, what is a special challenge for the design. At later periods, fluid pressure will be increased by convergence. In the repository system a two phase flow of liquids and gases is expected. The fluid pressure changes will be often linked to fluid flow processes. Those processes will impair the EBS function by channeling the backfill and the concrete seals. Advection, dispersion and diffusion are important processes for radionuclide transport.

Especially in the infrastructure area a broad spectrum of fluids with different hydrochemical properties have to be considered, e.g. a mixture of unsaturated groundwater from the surface and the overburden formations and different kinds of brine (Na, K, Mg / Cl, SO_4 concentrations) from the salt formations. Although different reference liquids are considered in barrier design by adequate construction materials, corrosion and alteration processes (e.g. concrete corrosion, microbial processes) can not be excluded during the future site evolution. This is caused by uncertainties in the prognosis of the hydrological-chemical evolution.

In contrast to the shaft seal subsystem, in the drift seal subsystem the heat flow from the disposal of high level radioactive waste is of highest relevance. This is explained by the smaller distance to the disposal fields. Geothermal heat flow (which is constant) as well as climate induced heat flow (only a temperature impact of 3-4 ℃ is expected) are of low relevance. The disposal of the heat generating radioactive waste will result in significant thermal-mechanical stresses (compressive strength) in the nearfield of the drift seal during the thermal phase, and tensile stresses after temperature decrease. Those stresses may result in fissures in the concrete constructions as well as loosening of the EDZ.

7.5.6 Radionuclide mobilization and transport

The second approach for developing the reference scenario addresses processes that are linked to radionuclide mobilization and radionuclide transport.

Radionuclide mobilization will take place in the disposal areas and will be the consequence of several casual chains of processes/events that will result in the failure of the waste package and the degradation of the different waste matrices.

Due to the specific assumption for the reference scenario that all barriers meet their design specific requirements there is only one reason for the failure of a waste package during the functional period: the existence of containers with undetected failures.

During construction as well as during quality tests mistakes will rarely occur. Those containers will fail as a consequence of lower impacts that are covered by properly designed containers.

After the functional period the failure of containers is expected resulting from mechanic, hydraulic and chemical impacts. Water can intrude a damaged container and then corrosion of the waste matrices (spent fuel, glass, metal, organics) and the mobilization of radionuclides will start. The chemical processes will also provide gas as another medium for radionuclide transport. The fluid-induced radionuclide transport by advection, dispersion and diffusion is influenced by the hydraulic properties of the mine excavations (including closure measures) and the host rock as well as on chemical processes like sorption, desorption, complexation, and colloid generation

7.6 Characterization of alternative scenarios

As described in above, there are three starting points for development of alternative scenarios. They are discussed in detail in Beuth et al. (2012). An important follow-up step in handling of alternative scenarios is the definition of comprehensive representative scenarios. Several alternative scenarios derived from different starting points may have similar consequences on repository system evolutions. For the procedure of performance assessment calculations it is necessary to define representative scenarios bundling and covering those similar alternative scenarios.

7.6.1 Deviations concerning the climate development assumptions

The reference climate development includes assumptions for climate cycles (approx. 100,000 years basing on astronomic Milankovic cycles)) as well as for intensity of glacials (Elster, Saale and Weichsel glacials) and warm interglacial periods. Those assumptions base on an analysis of the climate development in past and corresponding interpolations to future developments (actualism principle), Those prognoses have a high inherent uncertainty.

So the 100,000 years climate cycles were characteristic for the last 800,000 years, but in former times there were also cycles of 19,000-23,000 years and 42,000 years. Short climate cycles would result in in a new glaciation in the next 20,000 to 40,000 years. But investigations have shown, that shorter climate cycle durations correspond to lower temperature amplitudes between glacials and interglacials. Therefore glacier thicknesses are reduced, permafrost will only penetrate to smaller depths and glacial channels will only cut in the uppermost part of the overburden formations. Any significant impact on the host rock from those short glacials is not expected.

Other prognostic uncertainties rely on the characteristics on the glacial periods. So the site specific maximum thickness of the glaciers or the depth penetration of permafrost can not be predicted. Therefore conservative assumptions have to be taken as a basis for characterizing the progress and the characteristics of the glacial periods.

As the RANGERS study focuses on the performance assessment of geotechnical barriers whose functional periods are restricted to the time before the next glacial period (50,000 years), possible alternative scenarios for far future climate evolutions can be neglected here.

7.6.2 Deviations concerning the functionality of geotechnical barriers

A basic assumption for the reference scenario is that all technical barriers will work as required. Therefore in the alternative scenarios, the failure of a geotechnical barrier has to be assumed. A short overview of the corresponding scenarios for the different kinds of geotechnical barriers and their consequences on repository system evolution is given below.

Those scenarios do not analyze the reasons for the barrier failure (they can be analyzed by the impact of initial FEP (compare Tables 7-1, 7-2, 7-3) (apart from human mistakes or construction failures)) and – in a conservative manner – take no credit from the redundancy of the different elements of the geotechnical barriers consisting of several abutments and sealing elements. As a top down approach they describe the consequences on the repository system evolution.

The barrier failure scenarios suppose a higher hydraulic conductivity for the entire barrier construction. This may result from construction failures and/or a higher hydraulic conductivity of the contact zone and/or the EDZ. Beuth et al. (2012) proposed to take the permeability of the EDZ, fissures or porous media with high porosity as reference scales for the increased hydraulic conductivity of the failed barriers. This would correspond to a hydraulic conductivity 3 or 4 times larger than for the intact barrier. Synchronous, not casually linked failures of several barriers can be excluded (a combination of two events with a low probability is improbable).

To evaluate the most severe consequences for repository system evolution, an early point in time is assumed for the barrier failure scenarios. A relevant boundary condition at this time is that the compaction of the backfill is not yet finished.

Failure of a shaft seal: A broad spectrum of processes as well as human mistakes or construction failures may affect the functionality of the shaft seals (see initial FEP in Table 7-2). As a consequence a groundwater flow from surface, overburden formations and/or reservoirs in the salt formations via the shafts can be initiated towards the underground infrastructure area. Therefore all processes in the repository mine that are influenced by water and hydrochemistry will be triggered and intensified. The most relevant consequences on repository system evolution would be:

The unsaturated groundwater entering via the shaft will start leaching the surrounding salt formations. This process will continue up to the saturation of the groundwater. As a consequence, void volumes at the shaft and the infrastructure chamber contour will be generated and fractures and fissures in the adjacent host rock may be elutriated. This may impair the stability of the host rock in this area. As a consequence, flow paths to brine reservoirs in the host rock may be generated and the drift seal may be bypassed in parts. On the other hand, the high humidity would increase the creeping rate of the salt (convergence) and so contribute to the closure of void volumes.

Furthermore hydrochemistry will be modified and different alteration processes at the host rock and construction materials of EBS (e.g. concrete corrosion) may be initiated.

Due to the groundwater inflow the fluid pressure will be significantly increased. This brine will percolate through the drift seal and flood the disposal areas. Here, metal corrosion of the disposal canisters will be initiated. That's also relevant for radionuclide mobilization. Fluid inflow as well as gas generation due to metal corrosion, are important for flow processes in the mine excavations and therefore for radionuclide transport.

Failure of a drift seal: Due to the drift seal failure (and the not yet compacted backfill with a higher hydraulic conductivity). There is a flow path from infrastructure area to the disposal fields and vice versa. Relevant consequences of this scenario on repository system evolution would be:

The fluids in the infrastructure area have a diverse hydrochemistry. Therefore leaching of the salt formations and concrete corrosion at the barriers will be induced. Both processes may result in bypassing / malfunctioning of the drift seal. The fluids at the side of the disposal fields are saturated with the salts in the surroundings. The disposal areas are sited in rock salt formations with a low humidity. Brine pockets in the salt formations with a fluid volume of several hundred cubic meters are rare. Therefore the hydraulic loads at both sides of the drift seal will be different what is a challenge for the drift seal design.

The brine passing the drift seal will initiate intensive metal corrosion at the waste containers in the disposal fields and intensive gas generation will be initiated. This causes an additional fluid pressure at the drift seal. Due to the gas generation, a fluid flow back to the infrastructure area will be initiated. The high gas induced fluid pressure in the infrastructure area may impair the shaft seal. If the gas flow rate through the drift seal is lower than the gas generation rate, the gas pressure will exceed the minimum principle stress in the host rock and permeation into geosphere will start. Waste packages will fail due to corrosion. Radionuclides will be mobilized and transported through the underground excavations via the shaft.

Failure of a borehole seals: For surface exploration drillings there is a safety pillar between the boreholes and the underground mine excavations. That means, even after the failure of the borehole seal, there is no connection to the underground excavations and therefore no impact on the mine has to be considered.

That is different for underground exploration boreholes that are drilled from the mine excavations. A failure of the borehole seals of those drillings would have different consequences depending on their locations and geological boundary conditions. The most relevant types are:

Underground drillings connecting reservoirs in the host rock: Depending on the fluid volume and the hydrochemistry of the fluids, different chemical, hydraulic and mechanical processes can be initiated in the mine openings in the case of drift seal failure.

Underground drillings connecting different mine openings: Those drillings may form new flow paths in the mine excavations and even bypass the drift seals. Thus a fluid flow from the infrastructure area to the disposal areas may be facilitated and intensified or a release of possibly contaminated fluids from the disposal fields towards the infrastructure area and the shafts will be enabled.

The consequences of both system evolutions can be included in the alternative scenario “Failure of a Drift Seal”, that is described above.

Unknown geological characteristics: Due to limitations of measuring precision, malfunctions or human errors in analysis or interpretation of measuring results, some geological properties that will impair the rocks barrier function, may not be recognized. Due to mechanical, thermal-mechanical and chemical (leaching) processes, flow paths can be generated between the unknown reservoirs and the mine openings. So, for the corresponding alternative scenarios, the occurrence of brine pockets in salts, fracture reservoirs in anhydrite and fractures and faults with a high hydraulic conductivity are important. If they are not correctly identified, safety distances may not be kept and connections to the mine openings may be generated during repository system evolution. Furthermore the humidity of the salt rock due to fluid inclusions may be higher than expected. With regard to the consequences, the position and volume of the reservoirs and fractures/faults in the repository mine is crucial. Fluid inclusions are of special relevance for the disposal areas.

The consequences of unknown geological characteristics are similar to the failure of the geotechnical barriers. Therefore such evolutions are also subsumed in the corresponding scenarios.

7.6.3 Alternative characteristics of the initial FEP

As summarized in section 7.2 processes were identified that may directly affect the function of the geological and geotechnical barriers. For the reference scenario it has been assumed that the CRZ will not be impaired by those processes in expected intensity (earthquake, subrosion, permafrost, permeation of fluids in salt formations). The geotechnical barriers will be designed to resist the loads from the initial FEP in expected intensity.

Even if alternative characteristics are assumed for the geological processes, the safety function of the CRZ will not be impaired.

That is different for initial FEP affecting the geotechnical barriers:

- Migration of bitumina: if the bitumina will leak from the sealing element and migrate via fractures and faults in the surrounding rock, the sealing function of the shaft seal will be significantly reduced.
- Metal corrosion: the shaft lining includes a steel shell. The corrosion of the steel would modify hydrochemistry, what may affect the swelling capacity of the bentonite. Thus the sealing function of the shaft seal is compromised.
- Swelling and shrinking of bentonite: to assure the sealing function of the shaft seal an adequate water saturation and swelling of the bentonite is necessary. The bentonite swelling forces the fixation of the shaft seal in the shaft column and reduces the hydraulic conductivity. If swelling is reduced or if shrinking occurs, the sealing function of the shaft seal is reduced.
- Swelling, shrinking and creeping of concrete: concrete swelling closes the contact zone and initiates the closure of the fissures in the EDZ. Additionally the barrier is fixed in the cross section of the shaft or drift. Shrinking and creeping of concrete may influence the barriers properties unfavorably.
- Convergence: the salt creeping is an important process for fixation of a barrier in the cross section of a mine opening as well as for closure of the contact zone and the EDZ. If convergence rate is lower than expected, the required fixation of the EBS will only be reached with delay.
- Mechanical stress changes: the EBS is designed for expected mechanical loads (e.g. litho- and hydrostatic pressures, earth quake, thermal-mechanical stresses, swelling pressure of concrete or bentonite). If higher mechanical stresses occur, fractures may be induced in barrier components and thus the mechanical stability and the sealing function is impaired.
- Hydraulic stress changes: the EBS is designed for expected hydraulic loads (e.g. hydrostatic pressure, predicted gas generation). If higher hydraulic stresses occur, fractures may be induced in barrier components, which impair the function of the barrier
- Displacement of sealing elements: The swelling of the construction materials (e.g. bentonite, concrete) , will result in a displacement of a sealing element in the shaft. If those movements are more intensive as expected, marginal flow paths may be generated at the shaft contour.

- Setting and compacting of backfill and sealing materials: In the shaft seals, gravel columns are used as abutment. By gravel properties the compaction is limited to very small values and then does not affect the barriers function. But if compaction is significantly higher than expected, the shaft seal is not fixed in its installation location and therefore may be impaired in its function.
- Corrosion of concrete and material with Sorel phases: Different kinds of concrete are provided as sealing elements and abutments in shaft seals and drift seals. The functionality of those barrier components will be significantly reduced by corrosion.
- Dissolution and precipitation of salt minerals: crushed salt is used as long term sealing in shaft seals and drift seals. If MgCl-brine or only partly saturated liquids from the overburden intrude the crushed salt layers they may be partly dissolved and thus their function affected. The same process may also occur in the EDZ.
- Microbial processes: microbial sulfate reduction may contribute to concrete corrosion and additionally occur in the EDZ. This alteration process will modify the hydraulic properties of the material.

If considered with unfavorable characteristics all processes mentioned above may result in an impairment or failure of a EBS. Therefore the detrimental impact of those processes and the consequences of repository system development can be analyzed in the two alternative scenarios described in the previous section :

- failure of a shaft seal, and
- failure of a drift seal

7.6.4 Alternative characteristics of the initial FEP mobilization and transport of radionuclides

For the evaluation of the radiological consequences of repository system evolution, the FEP RN mobilization as well as radionuclide transport in the liquid phase and RN transport in the gas phase are of highest relevance.

With regard to radionuclide inventory, uncertainties may occur in terms of their chemical form (e.g. gaseous or easily mobilized). Considering radionuclide mobilization, hydrochemistry is very important, first for corrosion of the waste container, and second for the alteration of the waste matrix. For hydrochemistry a band width has been defined resulting from uncertainties with regard to concentrations, composition and distribution of the constituents. Therefore, if hydrochemistry deviates significantly from the boundary conditions assumed for design and closure planning, an early failure of the waste container may occur and corrosion of the waste matrices (metal, glass, organics) may also be enhanced. Corrosion of waste matrices is combined with radionuclide mobilization. The hydrochemistry and the amount of free water also influences the intensity of gas generation induced by the corrosion process. Gas is an important transport medium for volatile radionuclides.

Radionuclide transport relies on fluid flow and transport (advection, dispersion, diffusion) processes. The intensity of those processes depends on the hydraulic (porosity, permeability) and chemical (sorption, desorption, complexation, colloid generation, filtration) properties of the media flowed through (barriers, backfill, EDZ, host rock).

Therefore the alternative scenario on radionuclide mobilization and transport is closely linked to the alternative scenarios on the failure of barriers.

7.7 Summary

Out of the presented FEP and scenario analysis, a reference scenario and two alternative scenarios can be derived to analyze the design and the performance of the EBS. The reference scenario assumes an evolution of the repository as described in section 7.5. In this scenario, all technical barriers will work as expected. This scenario is described by the initial FEP as well as the process FEP describing radionuclide mobilization and transport. Only for this (reference) scenario, the integrity of the EBS has to demonstrated according to EndlSiAnfV (2020).

The alternative scenarios assume a failure of the components of the EBS. This is the case for the shaft and the drift seal. As has been shown in section 7.6.2, a failure of the shaft seal will cause an higher inflow of fluids from the overburden to the repository mine. A higher geochemically induced degradation of the sealing materials will be also intensified. A failure of the drift seal is combined with a higher water migration through the drift sealing elements toward the emplacement fields where a higher metal corrosion of the waste packages and consequently a higher gas transport and gas pressure build-up can be expected. For these two alternative scenarios, the integrity of the EBS has to be evaluated. EndlSiAnfV (2020) states in §4 (6) that , it shall be verified and demonstrated that the repository system retains its function during the assessment period for the alternative scenarios. EndlSiAnfV (2020) further requires in §12 (3) that It shall be ensured that measures for optimizing the repository system derived from alternative scenarios do not significantly impair the safety of the repository for the expected developments.

It follows from the requirements of the EndlSiAnfV (2020) that the integrity of the repository as whole, and of the EBS in particular, has to be *demonstrated* for the reference scenario. For the alternative scenarios, the integrity has to be *evaluated* with the aim at showing the robustness the system. These two approaches are the core principles underlying the safety and performance assessment of the EBS and they are well illustrated in Figure 7-3.

8 Abstraction of scenarios into model computation cases

Given the complexity and non-linear evolution the repository system, with numerous influencing factors, the safety assessment of the repository system can only be achieved based on numerical simulations. Scenarios form the foundation for quantitative safety assessment simulations, utilized for purposes such as integrity analysis or radiological consequence analysis. The conversion of the scenarios into numerical assessment cases is a non trivial task that demands careful thoughts because the described scenarios cannot be directly depicted and evaluated using a single numerical code.

To carry out the model computations, computation cases are defined, each of which represents model abstractions of the scenarios with defined parameter values, parameter ranges, or characteristics pertaining to the statistical distributions of the parameter values (Beuth et al., 2012). Each computation case takes into account the numerical code and the FEP assignable to that program. Therefore, a computation case can be understood as a numerical model of a sub-aspect of a scenario (Kock et al., 2012).

For the numerical analysis of the individual scenarios, multiple computation cases are typically defined. This is partially attributable to the fact that the multitude of processes to be considered in a scenario often cannot be completely depicted or dealt with using just one calculation program. Furthermore, depending on the safety-related issue to be assessed for a scenario (e.g., integrity analysis, long-term radiological analyses), it determines which calculation programs should be employed. Conversely, it is conceivable that a comprehensively defined computation case is suitable for evaluating the effects of two or more scenarios. In any case, it is crucial to demonstrate the applicability of the computation cases for the respective scenarios, and ensure that the computation cases defined for a scenario collectively allow for a comprehensive assessment of all safety-related issues (Beuth et al., 2012). Figure 8-1 schematically illustrates the stages and elements, starting from the development of scenarios, their abstraction into computation cases, as well as the modeling and analytical evaluation. The overall appraisal of all results from the model computations is then performed in the synthesis report.

Some limitations arise however when the described scenarios cannot be directly depicted and evaluated using a calculation program. This may be due to certain processes not being depictable or only limitedly depictable in terms of modeling, perhaps because the process is extremely complex and the necessary calculation programs, tools, or data for modeling to the required degree of detail are not available. Alternatively, it could be because understanding of the process is less well-developed, resulting in uncertainties in the process description (Beuth et al., 2012). In such cases, further research and developments work is necessary to increase the understanding of such processes and to qualify numerical tools to take into consideration (Kock et al., 2012).

Another challenge is to demonstrate that the numerical analyses are comprehensive in terms of the processes considered and in terms of the completeness of the processes to represent a given scenario. Also, the interaction between the processes in the scope of numerical analyses should be considered. Kock et al. (2012) recommend to focus on the smallest possible number of representative cases, thus systematically generating comprehensive computation cases from scenarios. However, no general methodology for this process currently exists. This is especially due to the fact that all model computations incorporate simplifications (e.g.,

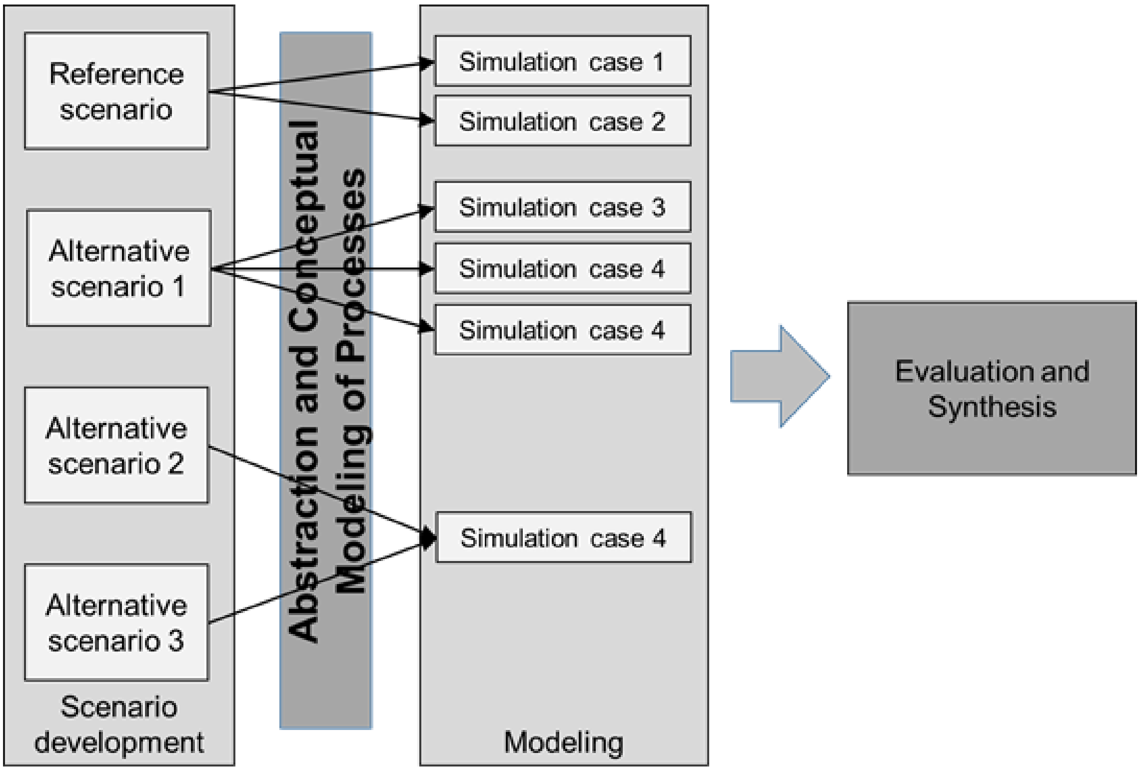

Figure 8-1: Schematic workflow describing the modeling of processes as intermediary step between the development of scenarios and PA simulations and Assessment after Beuth et al. (2012)

concerning the level of detail of repository systems). As already mentioned, not all processes are well understood and can be proceeded through computations.

In the scope of the Preliminary safety assessment of the Gorleben site (VSG), the strategy of abstracting scenarios into computation cases consisted on determining in a first step whether a FEP used in the scenario is relevant in terms of integrity analysis or radiological consequence analysis. Then, computation cases for integrity assessment were considered for modeling using different calculation programs, with which the scales and processes relevant to the integrity analysis can be considered. In an additional second step, it was examined which calculation program each FEP could be assigned to. The aim was to account for as many processes as possible occurring within the scenarios in the quantitative integrity analysis. This step also reveals which processes might require further research or development, especially concerning their implementation in numerical codes, primarily due to possible missing connections. Following that approach, it was possible to consider the majority of the processes and the scales relevant to the integrity analysis in different and carefully selected numerical codes so that computation cases comprehensively covered the considered scenarios (Kock et al., 2012). Figure 8-2 illustrates how the initial FEPs have been assigned to the different numerical codes guided by the premise of examining as many coupled processes as possible and covering the processes of the reference scenario with as few computation cases as possible.

As for the alternative scenarios that affect the EBS, they have to be considered during the radiological consequence analyses according to EndlSiAnfV (2020) in §4 (6). This does not imply

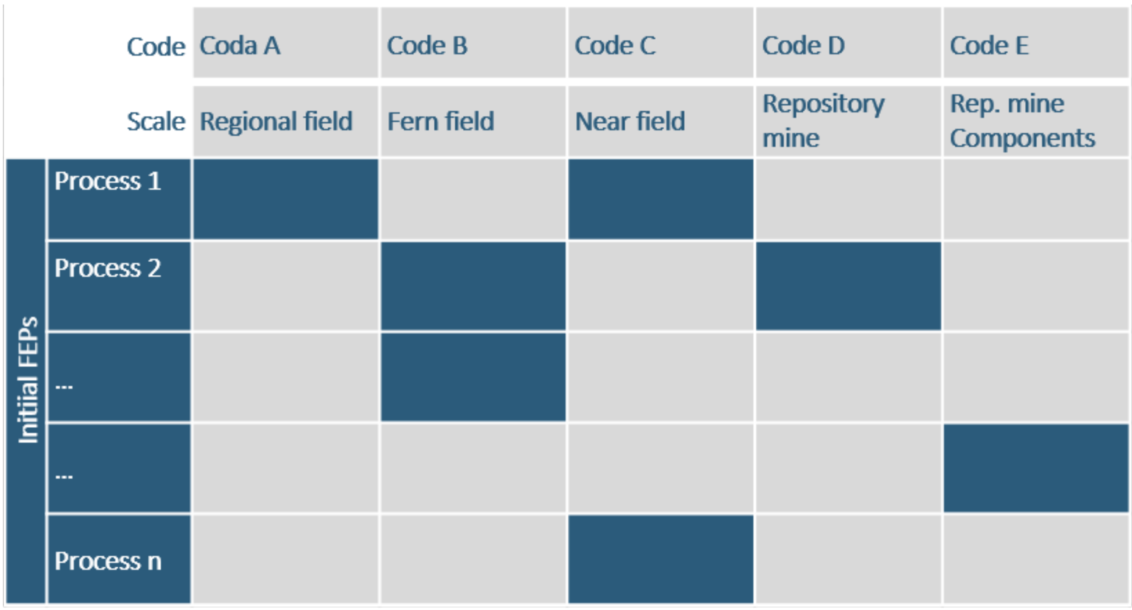

Figure 8-2: Assignment of initial FEP to numerical codes following Kock et al. (2012)

that alternative scenarios play no role in the integrity analysis. It is conceivable that even a less probable development could influence the barrier effect of the final nuclear waste repository. Therefore, those scenarios have to be considered in the scope of the integrity evaluation of the EBS. The analysis of the alternative scenarios also plays a key role in the optimization and the evaluation of the repository system in general and of the EBS in particular following the requirement formulated in EndlSiAnfV (2020) (§12 (3)). For this reasons, the hydraulic evolution of the shaft seal has been analyzed for the reference scenario and for the alternative scenario evolving a failure of the shaft seal. The objective was to verify whether the sealing system is fundamentally capable of preventing the access of surface, overburden, and formation waters to the radioactive waste, even in the event of a shaft seal failure. Additional objectives were to examine whether a sufficient temporal delay of the salt solution's occurrence in front of the drift seals is ensured, even in case of a shaft seal failure, so that the compaction of the salt backfill has progressed sufficiently. From this evaluation, it was possible to determine the pressure or pressure build-up rates as inner boundary conditions on individual sealing elements, which are examined in detail in the context of the in-depth integrity verification (Müller-Hoeppe et al., 2012a).

Based on the experiences gained from previous projects discussed above, one can derive the following rules in the abstraction of scenarios into simulations:

- The reference scenario is described by the identified initial FEPs. Thus the abstraction of these initial FEPs into simulations allows the numerical representation of the reference scenario. The more initial FEPs are considered the more complete will be the modeling of the reference scenario.
- The premise guiding the abstraction is to consider as many coupled processes as possible and to cover as many processes of the reference scenario as possible with as few computation cases as possible.
- The abstraction of scenarios into simulation is carried out based on the available com-

putational capabilities. Each computation case takes into account the numerical code and the FEP assignable to that program.

- Depending of the computer code at hand several computation cases are necessary to represent a scenario.
- Alternative scenarios that consider the EBS should be treated in the scope of the integrity evaluation and of the radiological consequence analyses. The abstraction of this scenario are not carried out by the initial FEPs but by representing the expected events that occurs when those scenarios arise.
- Initial FEPs and other processes that cannot be analyzed through modeling should be treated verbal argumentatively based on the actual state of knowledge covering these processes.

To follow these rules, the proposed methodology recommends the use of more realistic integrated models where most of the components of the subsystems to be analysed are explicitly considered in the numerical model. Those components are described in tables 7-2 and 7-3 for the subsystems shaft seal and drift seal. By applying this strategy, the interactions between the components are automatically considered. Initial FEPs affecting each of these components are to be considered during the numerical analyses by means for example of adequate constitutive models (e.g. use of a qualified constitutive swelling model to represent the swelling of bentonite) or by taking assumptions in the modeling to represent the effect of an initial FEPs in a specific component (e.g. representing the effects of swelling of bentonite by initializing the stresses resulting from the swelling effect in the bentonite component of the model). Components and processes that cannot be included in such an integrative numerical model can be treated in dedicated numerical analyses at the component level. The possibility to use surrogate models in the future represent a promising way to include the effects of complex processes into the integrated model. Implementing this strategy necessitates the use of extensive numerical models that range from the component level to the broad fern field level and requires high performance computing capabilities to cary out the simulation cased. This strategy has been tested in the modeling work package of the project RANGERS

9 Integrity Assessment

The goal of the Integrity Analysis is to determine whether the assumed developments of the repository system lead to loads that could compromise the integrity of the CRZ over the verification period (Kock et al., 2012). Taking into account the CRZ concept, the integrity analysis has to be carried out for the geological barrier and for the EBS. In each case, a verification concept is needed to evaluate the state of the barriers over the course of the repository evolution. The verification concept is derived from the safety concept which itself has to comply with the regulatory requirements. Based on the EndlSiAnfV (2020), a methodology for the verification of integrity of EBS in salt repositories is derived in this chapter.

9.1 Regulatory requirements

The secure containment of radioactive waste in salt repositories is ensured through the combined effort of the geological barrier and the engineered barrier system. The EBS is specifically designed to seal the rock mass that has been penetrated in order to install the repository. From the primary objective of protecting humans and the biosphere from the harmful effects of the disposed radioactive waste, fundamental object-specific requirements for the EBS arise. Those requirements are anchored in the regulations in force. In this regard, EndlSiAnfV (2020) requires that the properties of the technical and geotechnical barriers, which are relevant for the secure containment of radioactive waste, are maintained for at least the period during which these barriers are required according to the safety concept (§ 5 (1)). For the EBS, the primary properties referenced by the regulation is the sealing properties of the shaft and the drift sealing system as well as the sealing properties of the long term seal made of crushed salt in the repository mine.

Further requirements concerning the integrity of the EBS as part of the CRZ are formulated in § 5 (2) of the same regulation where it is stated that the integrity of the CRZ should not be significantly impaired by the development of temperature, and by possible changes in the chemical conditions in the repository.

Specific requirements for the geological barriers in § 5 (2) also apply for the EBS because the contact zone between the EBS elements and the geological barriers are a critical path that need to be verified in order to secure the safe containment of the CRZ. Therefore the dilatancy strength at the contact zone between the EBS and the rock formations in the CRZ should not be exceeded due to expected stresses (dilatancy criterion), and the expected fluid pressures should not exceed the fluid pressure capacities at the interface EBS/rock formations in a manner that leads to a significant increase in fluid pathways in the CRZ (fluid pressure criterion). The dilatancy criterion is used to assess the impact of mechanical damage to the rock mass caused by deviatoric stress, whereas the fluid pressure criterion takes into account the formation of flow paths driven by fluid pressure Kock et al. (2012).

One can summarize from these regulative requirements that the THMC evolution of the repository system should not endanger the sealing properties of the EBS embedded in the CRZ. From this premise, a specific integrity assessment concept for the EBS can be developed.

9.2 Basis for the design of EBS

Geotechnical engineered barrier structures are typically characterized by their layered construction. Within these structures, individual components fulfill various functions. Common components include sealing elements and abutments, complemented by backfill columns and filter layers. Depending on the specified requirements and system properties, these subsystems can be arranged in a diverse and redundant manner. For each of these components, specific safety functions are assigned. These safety functions dictate the different individual assessments to be carried out for each component.

Viewing geotechnical engineer barriers as geotechnical structures facilitates the direct application of engineering standards in their design and assessment. This approach is in line with the internationally recognized state of the art and is realized using the method of partial safety factors. The semi-probabilistic, reliability-oriented safety proof concept of partial safety factors is based on the Eurocode standards (DIN EN 1990, 2010) and is recognized in the construction industry for assessing load-bearing capacity. This method has been exemplarily applied to an element of a generic shaft closure in a previous research project (Eberth and Müller-Hoeppe, 2009), and within the preliminary safety analysis for the Gorleben site (VSG) for the design and assessment of the closure concept for shafts in rock salt (Müller-Hoeppe et al., 2012b,a). Another application example is contained in Kudla et al. (2013), demonstrating the assessment procedure using a sealing and a supporting element in rock salt.

The transfer of the practical construction approach to the assessment concept for geotechnical barriers allows the description of the structure and its properties in respective design situations by equilibrium states. The actual assessment is conducted through a limit state consideration, where the effects on the structure are compared with the resistances of the construction. Calculation cases arise according to the design-determining combinations of effects and system properties (similar to the load cases in the Eurocode) with which the limit state consideration can be carried out.

Referring to a limit state is sensible since both loads and resistances arise from typical distribution functions. The resulting scatter of both sizes leads to a range of possible states. The limit state describes the condition in the structure where the construction just meets the requirements and beyond which compliance with the design requirements is no longer given. Formally, to meet the requirement condition, it must apply that the resistances are greater or equal to the effects. The design values are determined from the characteristic values of the loads and the properties of the barrier in combination with the partial safety factors. This approach is illustrated in Figure 9-1. This procedure is applied to all loads and resistances.

Design values for individual assessments are derived from the characteristic values of loads and properties of the barrier, combined with the respective partial safety factors. By applying the method of partial safety factors, both the loads and resistances, or the included parameters of the target relationship, are assigned partial safety factors. Loads (E_d) are multiplied by the partial safety factors, thus increasing them. In contrast, resistances (R_d) are divided by the partial safety factors, thereby reducing them. This approach and the application of partial safety factors generally cover uncertainties in the representative values of influences and uncertainties in the construction properties.

Model uncertainties in loads and resistances are captured as necessary depending on the

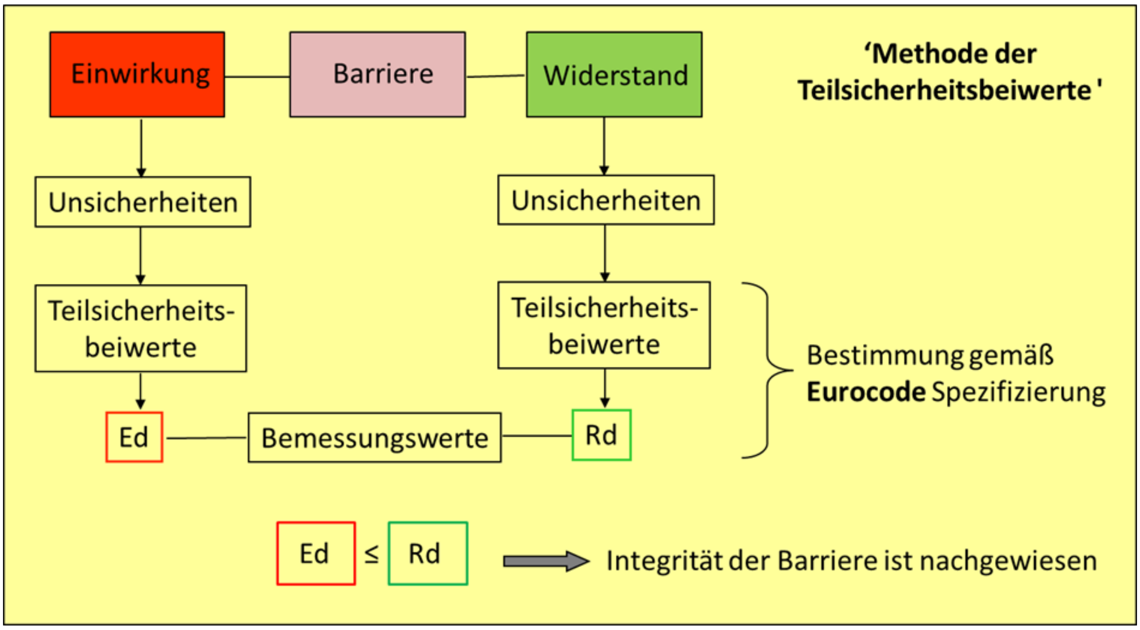

Figure 9-1: Basic principle of the method of partial safety factors (Jobmann et al. 2017b)

model formation via model factors. In cases of high accuracy of the models, model factors are typically not considered Eberth and Müller-Hoeppe (2009).

The basic requirement is

$$E_d \leq R_d$$

thus breaking down into concrete calculations for both terms. On the influence side, for E_d,

$$E_d = \gamma_{Ed} \cdot E(F_{di}; a_{di}; X_{di})$$

with F_{di} = Design values of various influences (i), a_{di} = Design values of the respective geometric sizes, X_{di} = Design values of the respective material properties.

The design values of the influence F_d are determined by multiplying the characteristic individual value (F_k) with the partial safety factor of the influence (γ_f).

$$F_d = \gamma_f \cdot F_k$$

For the design values of the material properties X_d, according to previous explanations,

$$X_d = (\eta \cdot X_k)/\gamma_m$$

with η = Conversion factor for load duration, humidity, etc., X_k = Characteristic value of the material properties, γ_m = Partial safety factor of the material property.

On the resistance side, the design resistance is derived from

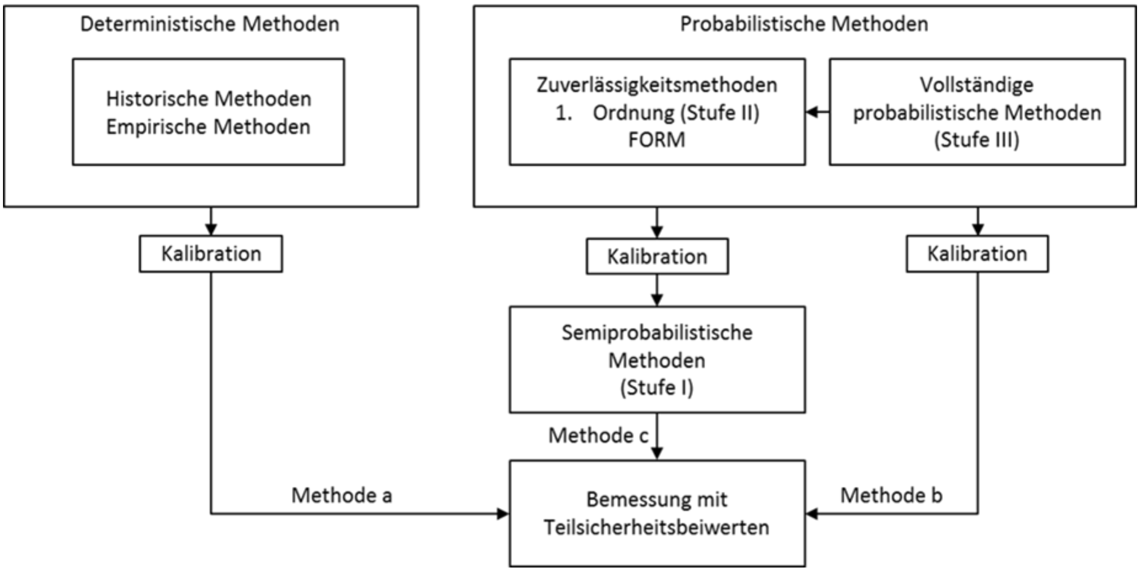

Figure 9-2: Reliability methods for determining partial safety factors (DIN EN 1990)

$$R_d = 1/\gamma_{Rd} \cdot R(a_{di}; X_{di})$$

with: γ_{Rd} = Partial safety factor for model uncertainty in the resistance model.

The individual verifications of the considered limit states are to be conducted "in the range of load-bearing capacity proofs", meaning that the reliability level of a load-bearing capacity proof is achieved. This safety concept is necessary to ensure a design that meets the requirements. For the considered structures, the proof of impermeability is seen within the range of a load-bearing capacity proof, as the loss of impermeability can pose a "danger to life and limb" (DAfStb, 2011). Unlike the definitions of the Eurocode, the term load-bearing capacity is not solely understood as mechanical stability. It serves as a synonym for preventing a danger to life and limb and can also be applied to hydraulic resistance. Adherence to the reliability level for load-bearing capacity in the respective proof ensures the functionality of the construction.

The application of an appropriate reliability level is necessary for a requirement-compliant design, as otherwise, a failure of the impermeability or structural integrity could pose a "danger to life and limb". This particularly affects the confidence level of the reliability proof. The probability of failure pf is sufficiently described for a load-bearing capacity proof with 10^{-4} over the intended use or functional duration (DAfStb, 2011). Thus, the functional proof includes that the barrier, over its lifespan, does not fail prematurely with a probability of failure pf $\leq 10^{-4}$, or the survival probability ps of the barrier is ps = 1 $-$ pf (Müller-Hoeppe and Krone, 1999).

The various influencing factors can be determined both through deterministic and probabilistic methods. For instance, the geometry of the construction results from the design, and loads can be identified based on statistical data and limit value estimations. Material properties can also be derived from a statistical basis (Müller-Hoeppe and Krone, 1999). If the current regulatory framework does not describe suitable partial safety factors, these can be determined through probabilistic methods or calibration (Kreienmeyer et al., 2008). Figure 9-2 schematically illustrates the methods for determining partial safety factors.

The technical regulations that can be used for assessment primarily include:

- Eurocode 0, Basis of structural design (DIN EN 1990, 2010)
- Eurocode 1, Actions on structures – Part 4: Actions on silos and liquid retaining tanks (DIN EN 1991, 2010)
- Eurocode 7: Geotechnical design – Part 1: General rules (DIN EN 1997, 2014)
- GDA Recommendations Geotechnics of landfills and contaminated sites (DGGT, 1997)
- DAfStb Guideline Concrete construction when dealing with substances hazardous to water (DAfStb, 2011)

9.3 Integrity assessment and verification concept of the EBS

As prescribed in the regulatory requirements, The EBS must exhibit sufficient hydraulic resistance during a defined functional period to prevent fluid transport into or out of the repository. To ensure the preservation of these properties over the functional period, the structural integrity of the construction must be demonstrated. If the barrier's resistances in a specific design case are sufficient against the impacts or combination of impacts, and if the feasibility of the construction is proven, then the functional verification is considered established. The basic structure of this proof is shown in Figure 9-3.

The basis for this proof is the conceptual design of the individual barriers, described in the sealing Concept. The subsequent verification is essentially divided into two steps.

In the first step, structural integrity verification must be provided for each individual barrier. To demonstrate structural integrity, the impacts or loads acting on each barrier after its construction must first be specified. This can be determined using the site-specific FEP catalog. From this catalog, those FEPs that describe an impact on the specific barrier can be identified. Once the FEPs and thus the impacting processes are identified, the impacts on each barrier can be specified.

In the second step, it must be proven that using all geotechnical barriers, including the backfill in the repository mine, the advection criterion can be maintained. For this purpose, the hydraulic resistances of all barriers and backfills are considered in conjunction, and it is examined whether the total hydraulic resistance is sufficient. In this context, and with a focus on the required redundancy and diversity of the barrier system, it is necessary to examine to what extent the failure of individual barrier components might affect the integrity verification. For this purpose, the hydraulic conditions must be specified. This involves the hydraulic resistances of all barriers and backfills, as well as the hydraulic gradients that will eventually establish themselves in the mine, as these drive the flow through the barrier system. If it can be demonstrated that the advection criterion is also met, then the verification of the integrity of the EBS is considered established.

Furthermore, (EndlSiAnfV, 2020) requires in §6 (4) that, It is to examine and demonstrate that the manufacturing and construction of the barriers, according to these specifications, can be quality-assured in the required quantity. The planned quality assurance must correspond to the current state of science and technology. The manufacturing and construction of the

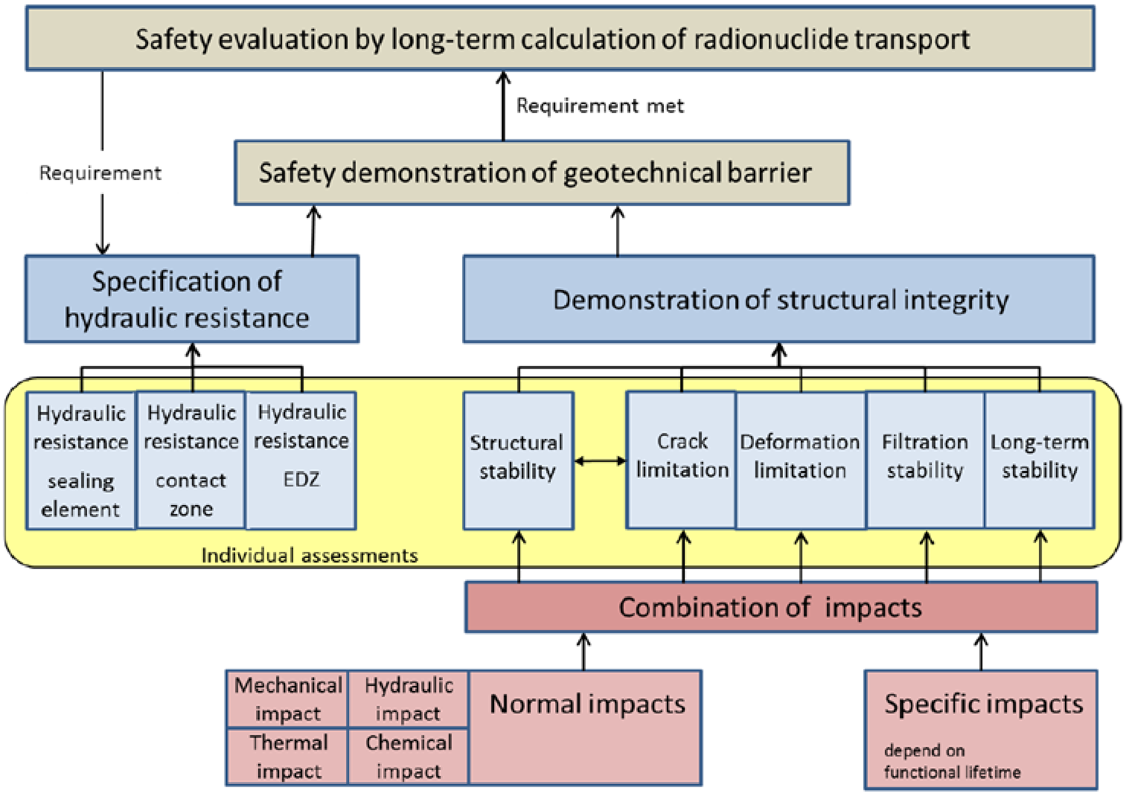

Figure 9-3: Integrity assessment diagram (Müller-Hoeppe et al., 2012b)

barriers must have been successfully tested under realistic conditions. Their function under these conditions needs to be examined and demonstrated. Consequently, a new criterion of constructability must be established.

The regulations in (EndlSiAnfV, 2020) mandate not only the demonstration of integrity but also the robustness of the Containment Rock Zone (CRZ), a requirement that extends to the Engineered Barrier System (EBS). The methodology presented herein offers insights into how the robustness of the EBS can be effectively demonstrated.

The following sections explain the individual proofs and the methodology used for verification

9.4 Demonstration of the structural integrity

The demonstration or verification of structural integrity comprises the following five individual verification criteria (Müller-Hoeppe et al., 2012b):

- Structural Stability (commonly referred to as “Load-bearing Capacity”)
- Crack Limitation
- Deformation Restriction
- Filter Stability
- Long-term Stability (also known as “Durability”)

Should any of these five individual proofs fail, the conceptual design of the respective barrier must be revised until all can be successfully demonstrated.

9.4.1 Structural Stability

Sealing effectiveness and load distribution are the two main functions of a geotechnical barriers. Within a barrier, these functions are assumed by different elements, typically assigning only one of these functions to each element. Load distribution and mechanical load-bearing capacity are functions of abutments, which can be cohesive or non-cohesive.

The load-bearing capacity of non-cohesive abutments, such as gravel columns in shaft closures, is primarily defined by settlement stability.

Cohesive building materials, like concrete abutments that develop adhesion within the material and with adjacent rock due to binders, are covered by the crack limitation proof for mechanical load-bearing capacity. For cohesive materials, any mechanical damage is always preceded by crack formations. If crack limitation can be proven for these materials, mechanical damage is ruled out, and the proof of mechanical load-bearing capacity is established. If crack limitation proof is unsuccessful, mechanical load-bearing capacity must be separately demonstrated.

The proof of crack limitation is established if no cracks occur in an abutment. If it can be shown that no damage occurs to a cohesive abutment during the analysis of loads acting on the concrete element, then the proof of crack limitation is considered fulfilled. If complete crack freedom cannot be demonstrated, then the limitation of cracks must be shown as part of the usability proof. For concrete, fracture criterion by Ottosen (1977) can be used for assessment. Accordingly, the criterion is defined as follows: It must be demonstrated that no significant damage occurs during the functional period within the verification period.

9.4.2 Crack Limitation

Crack limitation proof is relevant for both sealing elements and abutments. Crack formations are encouraged by mechanical overloading of individual subsystems (see above section) or thermal-mechanical-chemical processes during installation.

An example of crack formation due to volume or temperature changes is the cooling process of hot-installed bitumen or asphalt seals, where the sealing material undergoes cooling-induced volume shrinkage. As observed in practice, this shrinkage can reduce the effective sealing length of the seal by contracting and detaching from the contour in the upper part of the seal (Herold et al., 2020).

Depending on the sealing material used, crack formations could particularly arise from violating the fluid pressure criterion within the seal and its contact area and the corresponding limit states (Müller-Hoeppe and Krone, 1999). A violation occurs when the fluid pressure exceeds the smallest principal stress. An example is the large-scale experiment for a shaft closure in Salzdetfurth, where too rapid loading of a bentonite seal element damaged the seal (Teichmann et al., 2002).

The criterion for crack limitation is related to the fluid pressure criterion. This criterion stipulates, that it must be demonstrated that the effective principal stress σ_3' does not take on negative values.

For the computational proof, the following inequality must be shown to be satisfied:

$$\sigma_3' = \sigma_{3,\mathrm{ges}} - p_{\mathrm{Fl}} > 0$$

where

$$\sigma_{3,\mathrm{ges}} = \sigma_{3,E} + p_q + p_{\mathrm{Fl}}$$

with

- σ_3' = smallest effective principal stress [MPa]
- $\sigma_{3,\mathrm{ges}}$ = smallest total principal stress [MPa]
- $\sigma_{3,\mathrm{E}}$ = smallest total principal stress due to influences [MPa]
- p_q = effective swelling pressure of the bentonite [MPa]
- p_{Fl} = pore pressure [MPa]

9.4.3 Deformation Restriction

Engineered barriers are typically characterized by one or more sealing elements being held in position by abutments. This is especially necessary for swelling material seals. The swelling process of the sealing material only leads to sealing if the planned swell pressure within the seal is achieved. If the seal undergoes unplanned large volume expansion due to swelling, the planned swell pressure is not achieved. The abutments, especially in drift sealing systems, must therefore be deformation-stable and firmly anchored in the rock to ensure positional stability.

Especially for shaft closures, to ensure the positional stability of the seals, proof of sufficiently small settlements in the abutments and filter layers, which act as support for the respective seals, is required.

The proof of deformation stability involves demonstrating that the abutment itself is positionally stable and allows only minor expansion or deformation of adjacent sealing elements. In this context, (Wagner, 2005) noted that limited displacement of an abutment, for example, due to the swelling pressure of the bentonite, can be tolerated without causing a bentonite sealing element to become so loosened that its sealing effect is impaired. The criterion can be defined and quantified as follows: It must be proven that potential displacements of the abutment away from the bentonite sealing element are less than 3% of the length of the adjacent bentonite sealing element.

It should be noted that the investigations leading to the aforementioned 3% limit for displacement were conducted exclusively with Ca-bentonite (reference material). It is currently not ruled out that using a different type of bentonite, for example, sodium-dominated, might slightly alter this limit. This needs to be verified in the given case.

9.4.4 Filter Stability

The subsystems of individual closures, especially sealing elements made of granular materials, must be tested for their filter stability. This stability can be characterized by preventing erosion and suffusion processes in the considered subsystem. High hydraulic gradients due to fluid ingress from possibly existing aquifers can pose an increased risk of erosion and suffusion during the saturation phase. This must be countered by constructive measures. A lack of filter stability can, for example, lead to a reduction in the tightness of sealing elements.

When assessing the risk of material transport, a distinction is generally made between cohesive and non-cohesive materials based on the classification according to DIN 18196 (2011). Medium-plastic fine and mixed-grain mineral mixtures that possess effective cohesion are classified as cohesive materials. Coarse-grained and slightly plastic fine-grained mineral mixtures are considered non-cohesive materials.

Cohesive materials are significantly less sensitive to all forms of material transport compared to non-cohesive materials. Due to their internal binding forces, cohesive materials consist of interlocked and thus less mobile particles than non-cohesive materials. Under certain flow conditions, larger material parts, known as aggregates, can be dislodged from the composite. The risk of material transport decreases with increasing cohesion. Cohesive materials can absorb so much water at stress-free interfaces (e.g., at crack surfaces and cavities due to manufacturing defects or natural influences) that they almost completely lose their internal binding forces and thus their strength. In combination with flowing water, the risk of material transport increases (BAW, 2013b).

Clays or bentonites, from which sealing elements are made, are categorized as cohesive materials. In cohesive materials, individual particles are bound to each other by chemical and/or physical binding forces to the extent that individual particles are not freely movable. However, movable aggregates (group of interconnected particles) can form along weak zones in cohesive materials. The vulnerability of cohesive materials to material transport is significantly lower than that of non-cohesive materials due to the typically present aggregate size.

In the evaluation of filter stability, a fundamental distinction is made between two types of material transport: suffusion and erosion.

Suffusion refers to the rearrangement and transport of fine fractions of a material within the pore space of the coarse fraction's grain framework (BAW, 2013b,a). Here, the supporting grain framework remains unchanged, and no destruction of the material structure occurs. As a result of suffusion, the pore volume and permeability of the material increase, while its density decreases. With the increased permeability of the material, groundwater flow increases at a constant hydraulic gradient. Progressive suffusion can facilitate erosion processes if the stability of the supporting grain framework is reduced by the removal of fine material.

In order to prevent suffusion, the installation of filter layers has to be taken into account in the design process. The filter should not be designed to retain the entire fine and re-arrangeable grain spectrum. Otherwise, fine particles can deposit in front of the filter layer, reducing the hydraulic permeability. This increases the fluid pressure in front of the filter. The design of a grain filter for suffusive materials can follow the procedure by Lafleur et al. (1993). For the grain size distribution of the designed filter itself, proof against suffusion is also required to ensure the filter remains functional.

Erosion is defined as the relocation and transport of almost all grain fractions of a soil caused by water flow (BAW, 2013b,a), resulting in a change in the supporting structure. Erosion processes can pose an acute threat to the stability of an earth or massive construction. For the assessment of filter stability in sealing structures made of cohesive or binding materials, contact erosion and joint erosion are relevant. Internal erosion is covered by suffusion safety, and the proof against external erosion on the surface of a body is based on hydraulic calculations in the case of layer-parallel flow. This is not relevant for seals in underground drift and shaft seals, as layer-normal flow must be assumed in these cases.

9.4.5 Durability

According to the safety requirements (EndlSiAnfV, 2020), the integrity of the CRZ must be proven for the stipulated period of 1 million years. For the geotechnical barriers, a functional period must be defined in line with developments, during which their functionality must be ensured.

The definition of the functional period of the geotechnical barriers depends on the long-term development of the final repository system. In salt repositories, significant uncertainties exist regarding the compaction rate of the crushed salt and its permeability in compacted state relative to the degree of compaction. This is especially the case at advanced stages of crushed salt compaction, i.e., at very small porosities. Depending on the prevailing temperature and the presence of moisture, the compaction of the crushed salt until the required properties are achieved can take several decades to several thousand years. Due to these uncertainties, the design of the EBS is based on a target value for the functional duration of 50,000 years.

The integrity and verification concept is based on the EUROCODE, which was designed for structures with a service life of less than 100 years. This raises the question of whether the concept is viable for the defined service life of the EBS of 50,000 years. The only difference between a material used in standard technical constructions and one applied in a final repository lies in the required duration of the material's durability and its properties. While in typical technical applications, material durability needs to be proven for up to 100 years, in the context of a final repository, the durability and the material properties must be demonstrated for a significantly longer period up to 50,000 years. The key point to tackle this problem resides in the evaluation of the long-term stability of the materials used in the construction of the EBS. The design of a structure based on the EUROCODE concept is valid for higher functional time periods if one can show that the expected degradation of the material from which the structure is made is either limited or non existent under the loading, environmental and geological conditions to be expected.

In this regard, the long-term durability must be demonstrated for the entire respective EBS. In practice and according to regulatory standards, “durability” is defined as sufficient resistance of the material to environmental influences. The criterion is defined as follows: It must be proven that the properties of the elements of a closure structure are preserved over the defined functional period.

The durability or long-term behavior of the used materials can be evidenced by natural analogs. This is especially the case for clay and salt sealing materials used in the shaft and drift closure structures. These materials have a proven long term stability as the clay and salt geological formations have been formed several hundred millions years ago. In this regards, the dimensions of the sealing elements made of materials with proven natural analogs should be as large as possible to act as the natural analogs. An initial conclusion that can be drawn is that the thickness of the sealing element is a crucial factor. It has already been substantiated through historical analogs that particularly massive constructions tend to endure over long periods. A significant advantage in this context is the underground location of the sealing element. Historical structures located underground and made from durable materials often exhibit a high degree of preservation (Müller-Hoeppe and Krone, 1999).

For building materials where property-altering alteration processes are expected, such as cement-based concrete materials, geochemical analyses are necessary to evaluate or optimize the stability of the cement structures in contact with the groundwater solution to be expected in the repository over the functional period. For instance, it has been proven that Sorel concrete are geochemically stable in MgO-rich waters. Thus, it is therefore possible to design the EBS in such a way that MgO-rich waters can be expected in the repository. Materials like bitumen or asphalt, considered impermeable to liquids and gases, are also seen as long-term stable materials (Herold et al., 2020), but over a proof period of 1 million years, changes–for example microbial activities– cannot be ruled out, so functional periods must be defined for these materials.

9.5 Demonstration of hydraulic resistance

The hydraulic resistance or sealing or tightness criterion is applied in engineering and describes, in terms of the method of partial safety factors, the limit state of sealing (Müller-Hoeppe and Eberth, 2009): A barrier is considered tight if, during the functional period, the front of the infiltrating medium contaminated with pollutants does not reach the opposite front of the barrier. This definition provides a sufficient criterion for tightness. However, applying this criterion requires defining a verification period, as without it, the criterion remains indeterminate.

For geotechnical barriers, in accordance with the safety concept, a verification period of 50,000 years is established. Therefore, it seems appropriate to select an exposure period of 50,000 years for the quantitative demonstration of sealing. The position of the penetration front then provides a design criterion for proving sealing.

The required thicknesses of the sealing elements in the geotechnical barriers to ensure sealing are then determined only by the physical properties of the penetrating medium, such as viscosity, pressure, etc., and of the barrier, like permeability, porosity, saturation, etc. This reduces the task to determining the properties of the penetrating medium and ensuring the required barrier properties over the verification period (Müller-Hoeppe and Eberth, 2009).

In terms of the limit state of sealing, impacts on and resistances of the sealing structure must be determined. The impacts are characterized by the penetrating fluid and other FEPs that can affect the hydraulic transport through the sealing structures in the planned sealing site. The possibility of unfavorable deviations of impacts from their representative values is captured by a partial safety factor. The same applies to the possibility of unfavorable deviations of resistances from their representative values, where resistances are typically characterized by the representative values of material properties and the geometric data of the construction.

Partial safety factors generally represent factors by which the numerical expression of unfavorable impacts is increased or the numerical expression of resistances is decreased. The partial safety factor for material properties is introduced to consider the possibilities of unfavorable deviations of material properties from their characteristic values and a partial safety factor to capture unfavorable deviations of the geometric data from characteristic (set) values (of the construction) governed by tolerance specifications. Furthermore, a partial safety factor is conceivable to account for uncertainties in the design and assessment.

9.6 Demonstration of constructability

All components of a closure structure must be manufacturable or constructible under the local conditions of the planned sealing site. In this regard, the EndlSiAnfV (2020) requires in §6(4) that: The properties required for long-term safety of technical or geotechnical barriers must be specified in the safety concept. It must be examined and demonstrated that the production and construction of the barriers according to these specifications are possible with the required quality assurance. The intended quality assurance must correspond to the state of the art in science and technology. The production, construction, and function of the barriers must have been successfully tested, insofar as their robustness cannot be otherwise demonstrated and there are no safety reserves to an extent that would allow forgoing testing.

This leads to the following criterion: It must be proven that the closure structures can be constructed under the local conditions of the planned sealing site in such a way that their assigned performance objectives are met.

Fundamentally, the assessment can be conducted by comparing with similar structures that have been erected nationally or internationally and have been successfully tested. If comparable structures have not yet been constructed, the proof of manufacturability can also be provided through the execution of a large-scale in-situ experiment, which encompasses both the construction and the functional test. In this regard, the factors listed in DGGT (1997) should be appropriately applied to the assessment of underground closure structures and detailed. These factors include:

- Manufacturing prerequisites
- Handle-ability and sensitivity to errors of the manufacturing process
- Sensitivity of sealing materials to installation stresses
- Testability
- Possibilities for improvement and repair

In addition, a quality assurance program must be provided, which includes test plans describing the quality-assuring procedural steps and quality agreements describing the quality-assuring properties. The Eurocode (DIN EN 1990, 2010) notes that, if applicable, EN ISO 9001:1994-08 (1994) can also be used for quality management measures. In the case of barriers in a final repository, a comparison with the IAEA recommendations on quality management should also be made (IAEA, 2008). Only after the presentation of a feasible quality assurance program for the function-defining properties can the functionality of the individual barrier component be proven.

9.7 Demonstration of robustness

In EndlSiAnfV (2020) robustness is defined as the insensitivity of the safety functions of the final repository system and its barriers to internal and external influences and disturbances. Because, the proposed verification concept is based on the semi-probabilistic, reliability-oriented safety concept, the robustness of the EBS in the scope of integrity assessment can be analyzed by means of partial safety factors that affect the loads acting on the EBS and the properties of the materials (resistances) used in the EBS. In this regard, the safety factors account for the uncertainties of the EBS in the repository system.

The safety factors used in the design correspond to a specific probability of survival of the structure which is inversely correlated with a probability of failure. By decreasing, the probability of failure for the verification period, i.e 50000, one can increase the robustness of the system. For that, the safety factors need to be calibrated for the defined probability of failure. One refers to Figure 9-1 for calibration method of safety factors.

A different approach may consist in progressively increase the safety factors to determine the limit under which the system will collapse. This state corresponds to the lowest probability of failure of the structure. Such an approach is usually used in the design of tunnel constructions and it is called as phi-c-reduction (Itasca Consulting Group, Inc., 2021). In the context of the EBS with different materials involved in contact which different geological layers, this approach is more difficult to implement and requires a considerable computational effort.

Another method to explore the robustness of the system is through extreme state analyses. In this approach, parameters are chosen to be extreme – even 'unrealistically' so – in an attempt to push the system to the limits of its robustness (so-called what-if scenarios). This approach was pursued in the scope of VSG in several integrity assessment analyses. For example, in the thermal-mechanical calculations involving the mine structure, the heat input into the final repository was altered to very unrealistic values to test the behavior of the final repository system under extreme conditions. Similarly, unrealistically high values were used in the hydraulic calculations within the mine structure, for instance, for the fluid saturation of the backfill (Kock et al., 2012).

The limit state approach can also be combined with the semi-probabilistic, reliability-oriented safety concept. Such a combination is useful for the cases where the safety factors for specific impacts cannot be easily estimated. In this case, one can consider unrealistic manifestation of such impacts to assess the robustness of the system.

Another approach consists of determining the probability of failure the system through a fully probabilistic methodology. In this approach, the factors influencing the resistance and the impacts on the structure are described by the probability functions. The limit state analysis of the system are performed with Monte Carlo simulations to determine the robustness of the system. This approach has been employed by Wagner (2005) for the design of a shaft sealing structure in a salt repository. Although this approach represents the most complete one, it remains the most challenging due to the urge amount of simulation cases to be realized. It remains non practicable even regarding the rapid advancement in the development of numerical tools. Model simplifications are therefore necessary. On the other hand, this approach can be useful in the determination of safety factors that can be used in other methods discussed above.

In conclusion, the assessment of the robustness can be considered as part of the integrity evaluation as the system is pushed way above the safety criteria to be met in the scope of the integrity assessment. Different methods can be used to assess different specific cases. Those cases depend on the local situation at the planned sealing site. A combination of all the discussed approaches is also possible. The robustness evaluation requires a significant computational effort. Further work is necessary to determine how complete a robustness analysis can be performed with the available numerical tools of today.

10 Integrity evaluation

Integrity evaluation encompasses the integrity analysis for less likely repository evolutions. According to EndlSiAnfV (2020), the integrity of the CRZ (therefore of the EBS) is not to be demonstrated for the alternative scenarios. But those scenarios have to be considered in the optimization of the repository system as required in §12 of EndlSiAnfV:

> *The safety concept and technical design of the final repository must be optimized considering all circumstances with attention to the balance of measures to achieve the following goals:*
>
> 1. *The long-term safety of the final repository, particularly the quality of the safe enclosure of radioactive waste and the robustness of the final repository system, and*
> 2. *The optimization is complete when further improvement of safety can only be achieved with disproportionately high effort.*
> 3. *In the optimization of the final repository, in addition to the expected and alternative developments according to § 3 paragraphs 3 and 4, the hypothetical developments and developments based on future human activities according to § 3 paragraphs 6 and 7 must also be considered. It must be ensured that measures to optimize the final repository system, which are derived from alternative developments, do not significantly impair the safety of the final repository for the expected developments.*

Based on these requirements, the integrity evaluation is considered in the proposed methodology by providing essential insights about the robustness and the optimization of the EBS. In our understanding, only the alternative scenarios are relevant for the integrity evaluation of the EBS. Less likely scenario such as human intrusion or other hypothetical scenarios occur independently of the EBS.

By focusing on the alternative scenario, one already assumed that the integrity of the EBS is partly not verified. In this case the integrity evaluation does not considered the structural integrity of the EBS but focused only on the hydraulic resistance of the EBS under harsher conditions, i.e. when only a part of the EBS is still functional. From the FEPs, the main alternative scenarios affecting the EBS are the failure of a shaft seal, and the failure of a drift seal. The evolution of the repository for such conditions is the main objective of the integrity evaluation.

In the past, the integrity evaluation was considered in the radiological long-term assessment. According to BMU (2010), the maintenance of the integrity of the CRZ must be demonstrated for probable developments. Less likely developments, as per BMU (2010), should be considered within the framework of the radiological long-term assessment. It is conceivable that even a less likely development could influence the barrier effect of the CRZ. Any change in the barrier effect must then be taken into account in the radiological consequence analysis (Kock et al., 2012).

In the propose methodology for the EBS, we propose to separately evaluate the EBS within the repository system independently of the radiological evolution. Although the methodology for performance assessment is also applicable for the integrity evaluation. This is especially the case because the advancements in the development of numerical tools for performance assessment allow the simulations of complex models at repository scale. In this regards, the modeling of the EBS can be integrated in a model dedicated for the performance assessment of the repository system.

10.1 Methodology for performance assessment

Performance assessment plays a critical role in the safety case for a waste repository, as emphasized by the US NWTRB (Nuclear Waste Technical Review Board). It is primarily aimed at a quantitative evaluation of post-closure safety, through a thorough analysis of repository performance and a comparison of this performance with quantitative design requirements and safety standards. Additionally, it estimates how quantifiable uncertainties may influence repository performance (MacKinnon et al., 2012).

This type of assessment necessitates both conceptual and computational models that encompass the pertinent features, events, and processes (FEPs) that are or could be significant to safety. These models need to accurately capture the physical, chemical, and biological processes that might occur within the repository system over its lifetime and beyond. This requires a deep understanding of the repository design, the waste being stored, the geological environment in which the repository is located, and the potential interactions between these components.

Essentially, performance assessment seeks to understand and quantify the behavior of a waste repository under various scenarios, including both expected and less probable evolutions of the repository system. By comparing these findings against safety standards and design requirements, it is possible to determine whether the repository is safe for long-term storage of waste and to identify any areas where further investigation or design changes may be needed.

Following MacKinnon et al. (2012), a thorough performance assessment includes quantification of the long-term, post-closure performance of the repository, the evaluation of uncertainties and the comparison with safety requirements. Figure 10-1 illustrates the performance assessment methodology that has been used in the certification of different radioactive waste repositories in the US like the WIPP defense TRU waste repository (U.S. Department of Energy, 1996) and the Yucca Mountain License Application (U.S. Department of Energy, 2008). This proven methodology is now the starting point for further development in the safety assessment of future repositories especially in salt.

The PA approach depicted in Figure 10-1 brings together different sets of data to provide confidence in the safety of the system after closure. This encompasses: (1) the fundamental technical groundwork for the safety evaluation models, akin to some safety case concepts like the assessment basis (see, for instance, (Nuclear Energy Agency, 2004); (2) an exhaustive analysis of scenarios and FEPs, ensuring a robust evaluation of post-closure performance; (3) a quantitative and qualitative description of the sealing functions of the barriers; and (4) analyses of uncertainties and sensitivities, pinpointing areas needing more data for the subsequent phase of repository advancement (MacKinnon et al., 2012).

A conceptual model framework requires a coherent representation of all pertinent FEPs. The

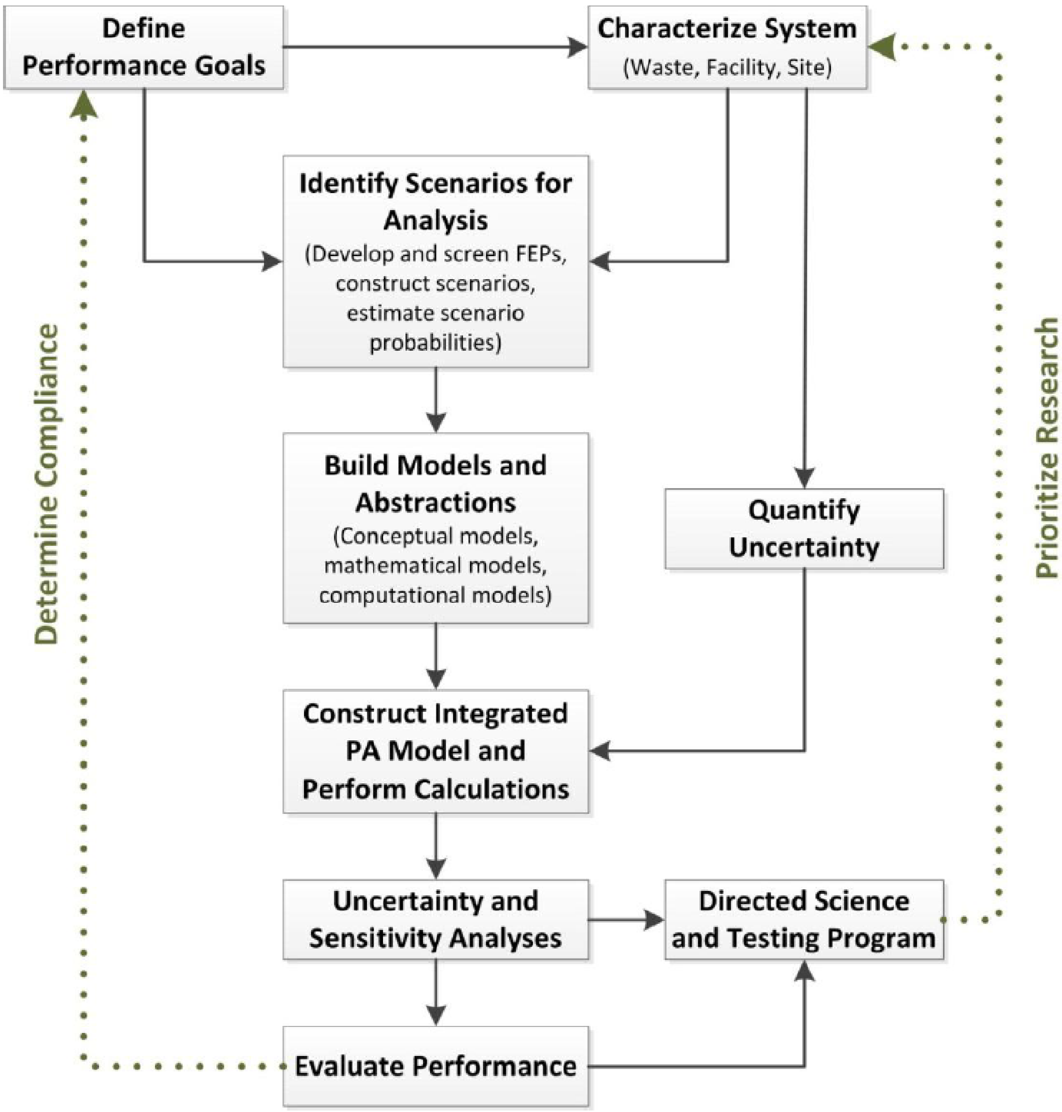

Figure 10-1: Performance assessment methodology (MacKinnon et al., 2012)

features of a conceptual model are the physical components of the engineered barrier system (EBS) and the surrounding natural barrier system (NBS). Primary features include radionuclide inventories, waste forms, waste packages, buffer materials, seals, drifts, shafts, host rock, surrounding stratigraphy, groundwater, fractures, aquifers, wells, springs, soil, etc. For implementation in a PA model, the conceptual model framework provides information regarding repository layout, e.g., the sizes and locations of waste packages, drifts, buffer/backfill, shafts, and seals. In addition, the conceptual model provides information beyond the repository to describe the dimensions, properties, and locations of important features in the surrounding geosphere and accessible biosphere.

Important processes and events in the conceptual model are those that could significantly affect the movement of radionuclides in the EBS and NBS. Such processes and events include waste package corrosion, waste form dissolution, radionuclide release, radioactive decay, heat transfer, aqueous transport, advection, diffusion, sorption, aqueous chemical reactions, precipitation, buffer chemical reactions, gas generation, colloidal transport, earthquakes, inadvertent human intrusion of the repository, etc. A FEPs database can be used to help identify a full set of potentially important FEPs for a specific conceptual repository model. Many of the FEPs in a FEPs database may be included in the PA model. In a comprehensive PA, excluded FEPs (i.e., FEPs not included in the PA model) must be addressed in separate analyses and arguments (Mariner et al., 2015).

10.2 The role of EBS in performance assessment in salt repository

The release of radionuclides from the host rock acting as an effective barrier (CRZ) can occur via diffusive transport due to concentration gradients or advective transport due to potential differences along two distinguishable transport pathways. This can either be the transport through the host rock unaffected by the mine workings or along the drifts and shafts excavated for the construction of the repository. In Salt, a transport through the host rock is only possible in the EDZ and in cases where the integrity of the geological barrier is not met. In this case, advective transport can take place through the fractured rock or in region where the salt dilantancy criterion is not met. In the case of an intact geological barrier which is to be shown in the scope of the safety integrity assessment of any specific site, only the second mode of transport through the backfilled drift network and shafts is possible. In these conditions, the confinement of the radioactive waste relies largely on the EBS. Essentially, the radiological evaluation of the repository can be limited to the region that has been excavated and later backfilled. Interaction with the geological layers takes place only in the EDZ surrounding the excavated volume. In this context, it becomes obvious to study with high accuracy how the fluid transport will occur during the evolution of the repository system in the repository mine and in the shafts as realistic as possible. Increasing the understanding of this process will help to better assess the potential of optimization of the EBS. This is exactly for this reason why the proposed methodology emphasizes an EBS centric PA assessment of salt repositories.

10.3 Performance Assessment modeling approach for the RANGERS project

Due the advancements in the numerical development of PA codes in recent years and the computational capabilities actually available, a modelling approach that is based on a direct coupling with process model codes used for the integrity analyses of the EBS is put forward. The core of this approach relies on a single highly detailed conceptual and numerical model of the repository system that resolves all components of the system going from the components of the shaft and drift sealing structures to the all geological layers. The simultaneous use of this performance and integrity assessment allows an implicit coupling of the two kind of assessments. Specifically, an implicit coupling can be established by transferring data from between the code. Thus, one can derive from the thermal-mechanical process codes in which the compaction of the crushed salt backfill in the drift system is computed, the porosity evolution in the repository that can be used to compute the permeability in the PA code for the fluid transport modeling at repository scale in PFLOTRAN. Conversely, the pressure build up of gases computed in the PA codes can be used to assess the as an influencing boundary conditions in the compaction analyses. The pressures of fluid computed in the PA codes can also be used as structural loads for the design and integrity of the shaft and drift seals.

11 Concluding Remarks

Rock salt is considered a highly suitable host material for the disposal of radioactive waste due to its unique combination of favorable properties. Its exceptional impermeability and low porosity effectively prevent the migration of radionuclides, ensuring long-term containment and isolation from the biosphere. The self-healing capability of rock salt, due to its plastic deformation under pressure, seals any microfractures that may occur, further enhancing the integrity of the repository system. Additionally, rock salt's thermal conductivity aids in the dissipation of heat generated by high-level waste, reducing the impact on the repository's structural stability. These characteristics, combined with the geological stability and widespread availability of salt formations, make rock salt an ideal choice for the safe and secure disposal of radioactive waste, providing a reliable barrier against environmental contamination for millennia.

The safe isolation of radioactive waste in rock salt formations depends on a multi-barrier system, with the engineered barrier system (EBS) playing a critical role. Since rock salt formations are naturally impermeable, any potential advective transport of fluids into or out of the repository can only occur through the EBS. Therefore, the EBS must be meticulously designed, utilizing sealing components strategically placed throughout the repository to ensure containment until the long-term sealing element, the crushed salt backfill, fully assume its safety function.

Within the framework of the project RANGERS, a methodology for the generic design and performance assessment of EBS in repository in salt has been developed. The methodology aims at describing a workflow on how to assess the integrity of EBS of generic repositories in salt and how to handle them in the scope of integrated performance assessments. It is based on the experience gained in Germany and in the USA in the design, construction, and evaluation of seals from several research projects.

The methodology developed aims at providing the necessary route to follow when designing and assessing the performance of the EBS in a salt repository. Based on the selected geologic site and the proposed repository concept, a sealing concept is defined from which the EBS results. The resulting repository system, which consists of the geologic site, the repository mine, and the EBS, is subsequently subjected to a FEP analysis. In this context, only the FEP related to the EBS are taken into account. From the FEP, the loads acting on the EBS are derived, which then serve as the basis for an integrity assessment of the EBS. Based on these FEP, the evolution of the EBS in the repository over the reference period is assessed. This is used to assess the performance of the EBS within the scope of integrated performance assessment simulations.

The methodology focuses also on the link between EBS integrity and performance assessment and helps to reduce the uncertainties concerning the treatment of EBS in PA modeling. It also brings an EBS-centric view on PA by focusing on the processes occurring at each component of the EBS and their evolution over the lifetime of the repository. The improved understanding of the repository system that can be gained from this approach will help to optimize the sealing concept for repositories in salt.

Based on this methodology, a modeling concept has been developed. The modeling concept allows deriving the numerical analyses that are required within the scope of integrity assessments in a stringent manner and carrying out safety assessments. The application of this methodology and the resulting modeling concept of the EBS is the subject of the modeling report of the RANGERS project.

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