Coupling of Performance Assessments and Integrity Assessments of Sealing Elements in HLW/SNF Repositories in Rock Salt – 25304

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ABSTRACT

Germany considers salt rock formations as one of the potential host rock formations for a future underground geological repository for the disposal of high-level radioactive waste (HLW) or spent nuclear fuel (SNF). However, an engineered barrier system (EBS) is essential to ensure the safety and long-term containment of waste in saline repositories. The assessment requirements of national regulations must be demonstrated to achieve structural and functional integrity during and after the disposal period. A major challenge is to account for significant geomechanical and permeability changes in the rock formations and subsequent changes in repository conditions in the safety assessment. Therefore, a comprehensive modelling methodology has been developed, emphasising geological sealing concepts and the use of scenarios based on FEP analysis. The safety analysis and results show that the modelling approach adopted is appropriate and reliable for the performance and integrity assessment of repositories in saline formations.

INTRODUCTION

The Engineered Barrier System (EBS) is essential for the safe, long-term containment of high-level waste (HLW) and spent nuclear fuel (SNF) in salt-based geological repositories. As part of a multi-barrier approach, the EBS complements the natural barrier of salt and the engineered barrier of disposal casks. Its primary role is to maintain containment during the initial period until the crushed salt backfill compacts to a state of low porosity and permeability, forming a long-term seal. During this compaction phase, the EBS is required to retain both its structural integrity and its functional integrity. In Germany, regulations require the EBS to function effectively for up to 50,000 years, potentially until the next ice age. Such a period introduces uncertainties due to significant hydro-geological changes that could alter the conditions of the repository.

To address these challenges, BGE TECHNOLOGY GmbH and Sandia National Laboratories, through the RANGERS project, have developed a comprehensive methodology specifically tailored for EBS design and safety assessment in salt formations. Follow up the development of a repository concept at a specific site, a sealing concept based on the geological characteristics of the selected site and the overall repository design is developed. A Features, Events and Processes (FEP) analysis is then carried out to identify the stresses that affect the EBS and form the basis for an integrity assessment. This structured approach allows detailed simulations to predict the evolution and performance of the EBS over time. By using this modelling approach, accurate and reliable safety assessments are achieved to support the long-term containment of HLW and SNF in saline repositories. This study applies the methodology specifically to the design and integrity assessment of a drift sealing system within a generic salt formation.

METHODOLOGY

The development of high-level waste (HLW) and spent fuel (SF) repositories in salt formations follows international safety standards, focusing on a comprehensive “safety case” for the overall system performance [1].

In countries like the U.S. and Germany, studies on salt domes (Gorleben site) and bedded salt formations (WIPP site, generic German sites through the KOSINA project) [2] have highlighted the favorable properties of salt for waste containment. Salt's properties offer safe containment by sealing radioactive waste within a specific zone, termed the Containment Providing Rock Zone (CRZ), which comprises natural geological barriers and engineered barrier systems (EBS). Over time, compacted crushed salt achieves a sealing capacity similar to that of intact rock salt, especially as it compacts due to host rock convergence, heat from radioactive decay, and moisture content. Until this process is complete, the EBS must retain its structural and functional integrity.

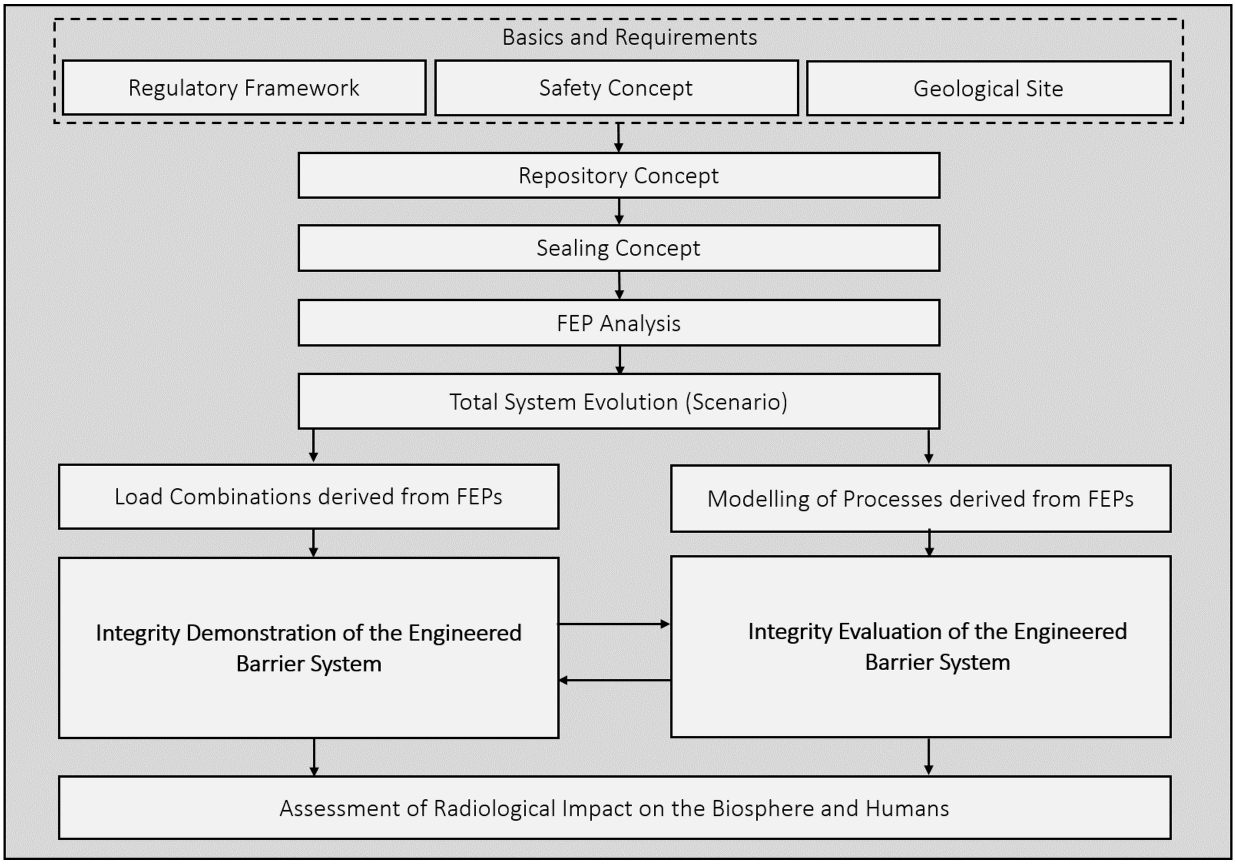

Figure 1 Methodology for the design, integrity, and performance assessment of EBS in repository in salt

This methodology, developed within the RANGERS project, provides a foundation for EBS integrity and performance assessment. It emphasizes key aspects during design, integrity verification, and integration into the total system performance assessment. This includes considering the regulatory framework in force, establishing a safety concepts and developing a repository design. The methodology also applies a standardized Features, Events, and Processes (FEP) catalog to describe system characteristics and future evolution, which informs the modeling scenarios used for numerical integrity and performance assessments [3].

The workflow for assessing the safety and integrity of a high-level waste repository system in a salt formation is structured into several stages, each building upon fundamental regulatory and geological requirements.

The Basics and Requirements stage establishes the foundational elements necessary for repository planning, including the regulatory framework, safety concept, and geological site specifications. Based on the basics and requirements, a comprehensive repository concept is developed.

This includes the configuration and placement of the repository within the salt formation. Subsequently, a sealing concept for the repository is developed to secure the repository against inflowing water and confine the radioactive waste disposed in the repository. This involves designing engineered barrier systems (EBS) and ensuring their integrity over their service lifetime.

The repository system's integrity must be verified under a reference scenario, as required by [4]. Less probable scenarios are assessed within a integrity evaluation, accounting for potential barrier integrity alterations. This dual-path integrity analysis framework — comprising integrity demonstration (reference scenario) and integrity evaluation (alternative scenarios) — provides a comprehensive understanding of repository robustness, as shown in preliminary Gorleben site assessments [5].

An FEP Analysis (Features, Events, and Processes) is conducted to identify relevant characteristics, processes, and potential events that might affect the repository system over time. This analysis feeds into the evolution modeling of the system. The results of the FEP analysis are used to simulate various scenarios representing the repository's evolution under different conditions, known as Total System Evolution (Scenario). The entire workflow described is schematized in Figure 1.

REPOSITORY AND SEALING CONCEPT

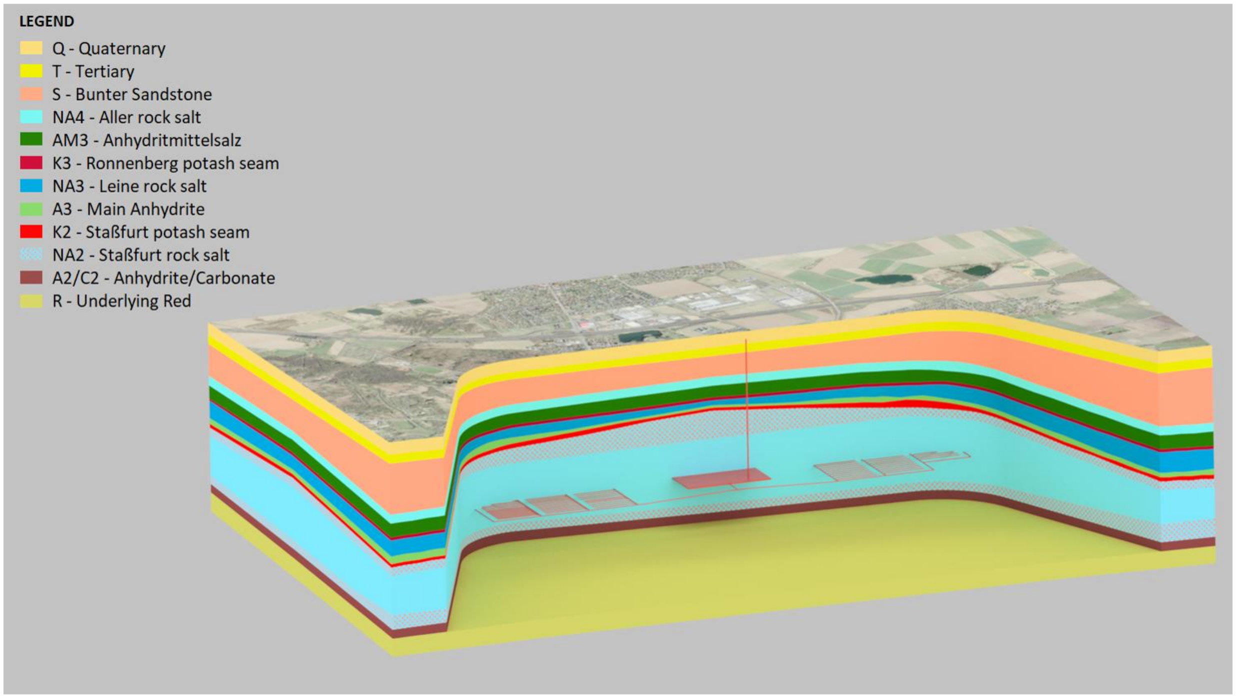

Figure 2 Generic repository system considered within this project (Courtesy of BGR)

As Germany has not yet selected a geological site for final waste disposal, this case study uses a generalized dataset of a salt pillow to represent the essential characteristics of the most promising basins. To develop this generic geological model, we first utilized the real lithology of reference areas [6] to derive a synthetic sequence of layers for the Stassfurt (z2) and Leine (z3) formations within the Zechstein evaporates [7]. Additional regional-geological data on the sedimentary sequence provided supplementary details for incorporating underlying rock layers and sedimentary formations atop the Leine Formation [2]. Through this approach, we identified a total of 18 regionally well-characterized lithostratigraphic units, subsequently consolidated into 12 homogeneous zones based on similar geomechanical properties.

The repository developed for this study involves the disposal of self-shielded casks in horizontal drifts, which are later backfilled with crushed rock salt. The layout includes two main emplacement wings, each 800 m wide, separated by a central infrastructure area containing two shafts. Each wing has three emplacement fields, with at least 250 m of undisturbed rock salt between the infrastructure area and the fields. The shafts are located in the thickest part of the salt formation.

In the southern section, three fields house POLLUX®-10 containers with spent fuel from pressurized water reactors (PWR). The northern section has a similar setup for reprocessed waste in POLLUX®-9 containers, along with a portion dedicated to CASTOR® containers for waste from prototype reactors. Two additional drifts near the infrastructure area store structural components from spent fuel assemblies in MOSAIK-II containers. The repository is designed for a 30-year operational period, with a maximum allowable temperature of 200°C on the waste cask surfaces. Figure 2 shows the developed repository mine within the generic geological model considered in RANGERS. An annotated view of the repository layout is given in Figure 3.

The repository design framework informs the planning of engineered barrier system. The drift sealing system, as designed within the RANGERS project, consists of a combination of abutments, drift seals, and a long-term crushed salt seal. In the repository presented here, four drift sealing systems are located in the two main drifts to close all access to the emplacement wings, as shown in Figure 3. The drift seals incorporate two MgO-concrete sealing elements, each bounded by concrete-based abutments to ensure mechanical stability and fix their positions. For geochemical stability, MgO-concrete is also used in the abutments. All elements are aligned in sequence, making direct contact with the surrounding rock.

It is recommended to remove the Excavation Damaged Zone (EDZ) as thoroughly as possible immediately before installing the drift sealing system [8]. At the installation site, the EDZ is expected to be 10 to 30 cm thick [9]. Any residual damaged zone remaining can be sealed by injection if necessary. But it is expected that the subsequent convergence of the rock will be enough for the recovery of the hydraulic properties in the EDZ. Between the sequence of sealing elements and abutments, an additional long-term sealing component made of crushed salt enriched with clay admixtures is included. The clay partially fills the pores in the crushed salt, reducing permeability at the early stages of compaction and accelerating the mixture’s progress towards a fully compacted state. Although the effectiveness of this novel material made of crushed salt and clay remains to be fully demonstrated, this study assumes that the mechanical behavior of crushed salt-clay mixture remains similar to that of crushed salt. Thus the available constitutive model describing the the long-term behavior of pure crushed salt is used in this study for the seals.

The long-term seal spans 300 m between the drift seals, while the MgO-concrete seals, including the abutments, extend over 115 m. Figure 4 illustrates the design of the proposed drift sealing system installed in the main drifts.

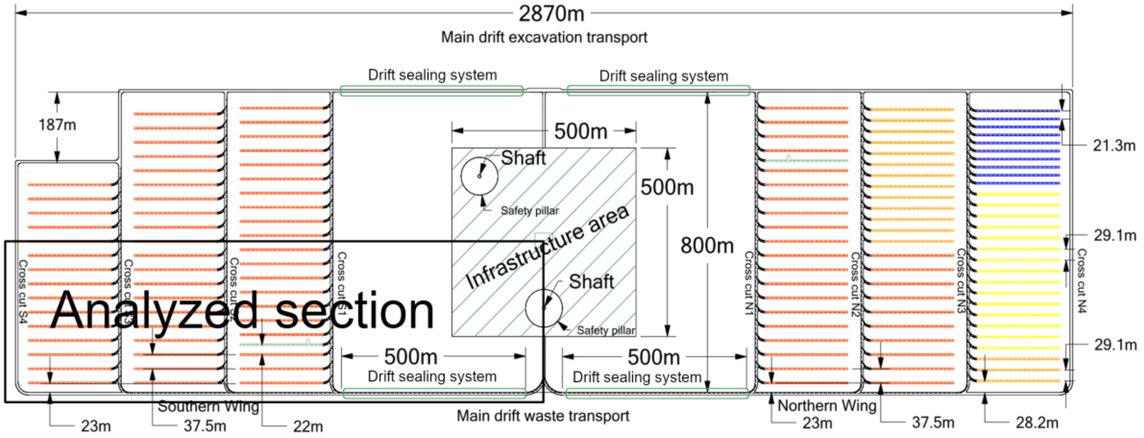

Figure 3 Layout of the drift sealing system in the repository mine at the drift level

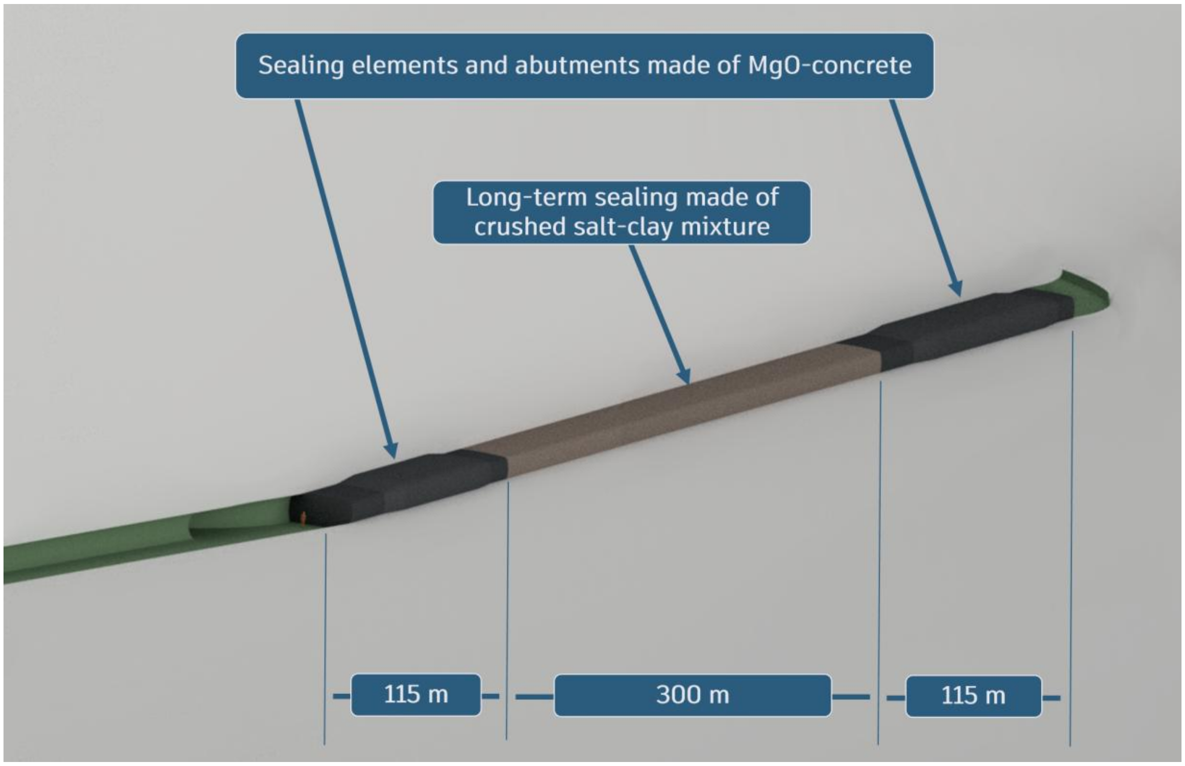

Figure 4 Illustration of the drift sealing concept designed for the present study

INTEGRITY DEMONSTRATION OF THE DRIFT SEALING SYSTEM

The integrity assessment is based on the loads derived from the scenario and Features, Events, and Processes (FEP) development. The FEPs relevant for the mechanical integrity of the drift sealing system were established in [9].

Among the FEPs relevant for the EBS, the thermal expansion and contraction, resulting from heat propagation within the repository, are among the primary loading conditions on the drift sealing system, aside from lithostatic load. The combination of heat flow and the convergence of the surrounding rock leads to mechanical stress changes throughout the repository, creating significant load scenarios that must be accounted for in the integrity assessment. Additionally, time-dependent processes such as swelling, shrinking, and creeping of the MgO-concrete used in the seals affect their resistance and must be considered. The combination of all these FEPs in a numerical model was the basis for the integrity demonstration of the drift sealing system.

Numerical model

The numerical model necessary to investigate the evolution of the drift seals accurately represent both the stress development and thermal propagation in the near field of the drift sealing system. Because the thermal sources are located in the emplacement field from which the heat starts to propagate within the repository, it's necessary to have a model that explicitly consider the emplacement fields. Thus, the model must cover an area of several square kilometers while consisting of finite elements that are only centimeters in size in key areas. To handle this complexity, the following simplifications were made.

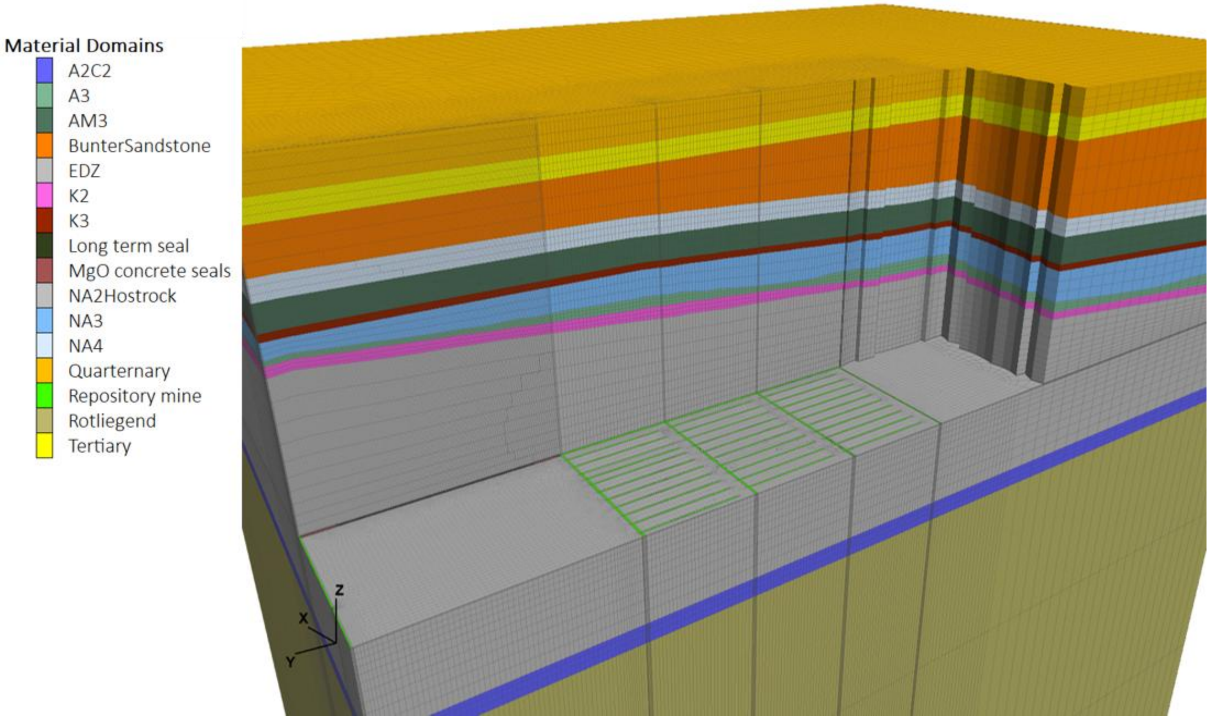

Figure 5 Isometric view of the numerical model of about 3 million elements for the compaction analysis of the crushed salt backfill in the repository

First, all the drifts in the model are simplified with a rectangular cross-section. The drift seals are instantaneously backfilled. This means that the pouring of the Sorel concrete made seals and the transient effects due to concrete hydration are not considered. The geological units above and below the rock salt formation are coarsely discretized which is sufficient to account for their weight and stiffness. Symmetrical boundary conditions were used, and only a quarter of the repository was modeled. The size of the finite elements varies in the model, ranging from 20~cm in the drift seals and gradually increases in the emplacement fields and in the overburden. The lateral boundaries are 1.5 to 2 km away from the repository, ensuring that minimal boundary effects are expected. The displacements were fixed normal to the lateral and bottom boundaries, and adiabatic boundary conditions were applied to the model boundaries.

The cross section of the drift seal in this model consists of 11 by 5 subdivisions. In this model, all the drifts are resolved and are used as heat sources with the corresponding thermal power of all waste packages disposed in each drift. The model is presented in Figure 5.

The modeling stages account in the simulation starts with the initialization of the primary state. It follows the excavation of the drifts in the mine, which is carried out instantaneously. A sequential backfilling is realized up to the complete closure of the mine. Thus, the main drift remains open over 30 years before the construction of the drift sealing system. Over the time, the convergence of the rock due to creep will compact all materials in the mine. This convergence process is further enhanced by the thermal propagation also considered in the model.

To limit the computational effort, the thermomechanical simulation was carried out over 1200 years. This corresponds approximately to the end of the thermal phase of the repository evolution. Subsequently, the thermal phase is deactivated and the simulation continue in the mechanical process class. This allowed us to speed up the simulation by a factor of 10. The residual heat still present in the model at 1200 years will enhanced the creeping behavior of the rock leading to more deformations and stresses on the drift sealing structure. This assumption is therefore conservative for the design of the drift seals in respect to their mechanical integrity.

Initial conditions

The drift sealing system is planned at the disposal level at a depth of 810~m in the Staßfurt sequence. An isotropic primary stress state is assumed, with an integral density of the overlying layers assumed to be 2,200 kg/m³. This results in a calculated depth pressure of approximately 18.5 MPa at the disposal level. For the undisturbed rock temperature, the temperature gradient of 3 K/100 m is assumed resulting in a temperature of 38.67°C at the disposal depth. At the upper boundary of the model, a constant air temperature of 9°C is assumed. At the ground surface, a convective heat flux (q_c) is considered with a heat transfer coefficient of ($\boldsymbol{\alpha}$= 8.7 $Wm^{-2}K^{-1}$ according to [11]). Thermally, the disposal of waste is represented by a transient heat source. Each disposal drift serves as heat source with the thermal power of the sum of the heat power of the disposal waste emplaced in each drift.

Constitutive models

To capture the complex behavior of repository system appropriately, the modelling of the drift sealing requires particularly various constitutive models in the modeling. The overburden, consisting of Quaternary, Tertiary, and Bunter sandstone layers, is represented using the Mohr-Coulomb failure criterion, suitable for sandy materials. For the salt formations, WIPP-derived creep laws are applied to capture the salt's viscoplastic behavior under long-term loading, with the WIPP law pre-implemented in FLAC3D for this analysis. The main anhydrite layer, typically fractured due to salt diapirism, is modeled with reduced stiffness to reflect its brittleness and plasticity, using the Mohr-Coulomb model.

The underburden below the salt is modeled elastically, as it is far from the drift sealing system and this approximation is efficient for the analysis. Used constitutive models and input elastic properties for geological layers, recommended creep classes for salt layers, and Mohr-Coulomb parameters for overburden and anhydrite are detailed in the report [10].

The repository will be backfilled with crushed salt, and a crushed salt-clay mixture will be used for the main sealing element between the Sorel concrete seals. Due to limited experimental data on this new material, it is initially assumed to behave similarly to crushed salt, though likely with lower initial permeability. Consequently, the crushed salt model from the report [10] is applied. The analysis does not account for the transient effects of Sorel concrete curing; instead, it focuses on long-term behavior, using the Drucker-Prager model calibrated to concrete strength at 56 days. Parameters are listed in Table 1. These parameters are characteristic values according to Eurocode.

Table 1 Material and model parameters used in the Drucker-Prager model for Sorel concrete

Property	**Units**	**Values**
Density, ρ	kg/m^3	1900.0
Elastic modulus, E	MPa	20333.0
Poisson’s ratio, υ	-	0.372
Bulk modulus, K	MPa	26475.26
Shear modulus, G	MPa	7410
Tension limit, σ_t	MPa	1.76
Friction-drucker, φ_φ	-	1.43
Cohesion-drucker, k_φ	MPa	5.6
Dilation-drucker, d_φ	-	0

Temperature and global displacements

The heat generated by radioactive waste is a key factor affecting the repository system, alongside excavation-induced stress redistribution. The temperature distribution in the model in Figure 6 (top) shows an increase of approximately 100 °C in the emplacement field at 700 years. This time point marks the maximum thermal peak during the repository’s evolution, after which the system begins to cool, and far-field temperatures gradually return to their initial conditions. At this stage, the repository begins to cool down, and temperatures in the far field start returning to initial geothermal conditions.

Figure 6 (bottom) displays the y-displacement distribution in the model at 700 years. Thermal expansion from the heated disposal drifts causes the surrounding rock to expand. This expansion is most pronounced in the first and third emplacement fields, as seen in the displacement patterns. In the first emplacement field (right side of the image), rock mass expansion occurs away from the emplacement, resulting in displacement opposite to the y-axis. In contrast, displacement in the third emplacement field aligns with the positive y-axis.

The second emplacement field, however, experiences minimal expansion. The expansions in the adjacent fields effectively constrain the second field, limiting its deformation. This interaction creates a stable zone with minimal displacement.

Figure 6 Temperature (top) and y-displacement (bottom) in model at 700-year time

Displacements and strains in the seals

Figure 7 illustrates the displacement vectors around the first Sorel concrete seal near the emplacement fields at the disposal level. The vectors represent the projected displacements on the x-y plane, excluding the z-component. As shown, the rock mass primarily moves in the y-direction at the level of the seal. Due to the viscous and creep behavior of salt, which deforms faster than the stiffer concrete seal, this rock movement generates lateral skin forces along the seal surface, inducing tensile loads.

Figure 7 Displacement vectors around the seal at 700-year time

This phenomenon is similar to "negative skin friction" in pile foundations, where settling soil exerts a downward frictional force on the pile surface, creating tensile stresses. Normally, skin friction between the pile and soil acts upwards, supporting the pile load. However, under certain conditions, this friction reverses, applying additional load on the pile instead of support. The settling soil exerts a downward force, effectively pulling down the pile. To verify this hypothesis, we analyzed the displacement of the seals throughout the simulation. Figure 8 shows the y-direction displacement for the two drift seals - one near the shaft and the other near the disposal side. It is evident that the seal near the emplacement fields experiences greater displacement than the one near the shaft. For both seals, displacement increases from the disposal to the shaft side, creating a heterogeneous distribution. This uneven displacement results in the elongation or extension of the seals, confirming that they are subjected to tensile stresses and validating the hypothesis.

Figure 8 Distribution of y-displacement in the drift seals over time

Stresses in the seals

The stresses in the seals resulting from the rock mass expansion are observed at several time points to understand the evolution of maximum principal stresses in both seals; the stresses responsible for the observed extension of the seals are exemplified in Figure 9 **Fehler! Verweisquelle konnte nicht gefunden werden.**. It shows the distribution of the maximum principal stresses in the seal, along with the vectors indicating the direction of these stresses. It is clearly noticeable that the maximum principal stresses are primarily in the tensile region at the evaluated time, and their direction aligns with the y-axis

— the same direction in which the extension of the seal has been observed. These findings further support the hypothesis that thermal expansion of the rock mass induces skin forces at the seal boundaries, leading to the development of tensile stresses and, consequently, the extension of the seals.

Figure 9 Maximum principal stress distribution and vectors in the drift seals at 750-year time

As can be expected, tensile stresses develop in the seals located near the disposal side and experiences higher stress compared to the one near the shaft, due to its closer proximity to the heat source, where thermal expansion is more pronounced. By around 750 years, the entire seal at the disposal side is subjected to tensile stresses with stress values exceeding 1 MPa in the seals.

Verification of integrity

To assess the integrity of the drift sealing structure, several verification criteria need to be evaluated. Those criteria are Structural Stability, Crack Limitation, Deformation Restriction, Filter Stability and Long-term Stability.

For the seals, we use the introduced Drucker Prager constitutive material model that has been validated and calibrated against experimental data. The evaluation of the damage state of the Sorel concrete based on this model allows us to quantify the criteria of structural stability and crack limitation.

Figure 10 Damage in the drift seals at the end of the simulation

Figure 1 illustrates the damage in the seals due to the thermomechanical behavior of the surrounding rock mass, shown along a vertical cut through the middle of the seal. As observed, the damage is confined to the ends of the seals (abutments). This damage results from the numerical artifact previously identified in the strain distribution, caused by the rigid contact assumption between the seal and the crushed salt. As the crushed salt compacts, it exerts traction on the seal that would not occur in reality. Using interface elements or introducing thin layers with weak thickness would better model the interaction between the seal and crushed salt.

It is also important to note that the damage is located in the abutment sections of the seal, which do not serve a sealing function but instead protect the sealing section, which remains undamaged. The amount of damage in the abutments is particularly related to the coarse mesh used for these analyses. This was necessary to limit the computational effort for the analysis. Using a finer mesh will to reduce the amount of damage in the abutments. This damage must be concentrated at the interface to the crushed salt as already mentioned. By employing an adequate numerical technique to realistically model the interface crushed salt/sorel concrete, one should not expect any damage at all.

Although the seals are subjected to tensile stresses, these stresses are not sufficient to cause any damage. As stress recovery progresses toward the compressive regime and the repository continues to cool, no further damage is expected in the long-term evolution of the repository. On the contrary, due to the compressive stresses that the seals will experience in the long term, the triaxial strength of the Sorel concrete is likely to increase, making the seals mechanically stronger than they were in the early phase after disposal.

Conclusion

The integrity demonstration of the drift sealing system involves assessing the thermal and mechanical responses of the sealing elements within the salt repository over time. Key loading conditions, such as thermal expansion from heat generated by radioactive waste and lithostatic pressure from the surrounding rock, create stresses that impact the drift seals. A numerical model was developed to simulate the seal's evolution, taking into account the complex thermal-hydraulic-mechanical-chemical (THMC) interactions within the repository. Displacement and stress patterns observed in the model indicate that the seals undergo tensile stress due to thermal expansion, resulting in controlled, localized deformation. Despite these stresses, the seals maintain structural stability, and any observed strain or damage remains within non-critical areas. This comprehensive analysis supports the drift sealing system's resilience and its role in maintaining containment integrity under expected repository conditions.

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