SEALING OF THE MORSLEBEN REPOSITORY, GERMANY

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ABSTRACT
In the context of the closure of the LILW-Repository Morsleben (ERAM) 26 drift seals must be erected. Being situated in the access drifts to the disposal areas these drift seals are of relevance to long-term repository safety. Their adequate hydraulic resistance has to be proved. The hydraulic resistance of drift seals depends on three main elements, the excavation disturbed zone (EDZ) of the drift, the sealing body and the contact zone between sealing body and the surrounding salt. To assess the hydraulic resistance of the EDZ and the sealing body a reliable data basis is already available. The data are given in this paper.

An adequate data basis is not available yet to rate the contact zone, however. To overcome this problem in situ tests are planned investigating the contact zone of the ten-year-old Asse seal. Additionally, laboratory tests will be performed using core samples from the Asse seal. The test program is described in this paper.

INTRODUCTION
In the German Democratic Republic the Bartensleben salt mine was selected in 1970 to serve as a repository for low and intermediate level radioactive waste. Following studies and the successful demonstration of the disposal technologies used an operational license was granted in 1981. Subsequent to German reunification on October 3, 1990 the Federal Government of Germany took over responsibility and the facility got the status of a federal repository. The license for operating the repository originates from the former German Democratic Republic and does not include the license for the closure of the repository. Therefore, according to the Atomic Energy Act (AtG) a license application for the closure of the repository has to be prepared by the Federal Office for Radiation Protection (BfS) who became the responsible operator of the repository after the reunification of Germany in 1990. The disposal of waste was terminated on September 28, 1998. Presently, a closure concept is planned, which matches the long-term performance requirements.

The ERAM is a twin-mine consisting of the concessions Bartensleben and Marie. It is 5.6 km long and has a maximum width of 1.7 km. The two shafts provide access to a widespread system of drifts, cavities and blind shafts between 320 m and 630 m below ground surface. The overall volume of the cavities amounts to more than 8 million m³, of which more than 2 million m³ had been backfilled mainly using crushed salt. During the operational period of the repository about 36,800 m³ of radioactive waste had been disposed off, mainly in the western field, the southern field and the eastern field, negligible amounts of waste were emplaced in the northern field and the central part.
The mine is located in the structure of the Aller valley zone, named after the small river Aller, covering an area of approximately 50 km². The salt body is characterized by an intensive folding of the layers and a high amount of anhydrite rocks, such as the main anhydrite ("Hauptanhydit") of the Leine formation (z3HA). Another feature of the deposit is the occurrence of potash seams which mainly are carnallitite and kiseritic hartsalz. In general, the evaporite layers and the tectonic elements, such as folds, follow the border of the structure.

The salt leaching surface forms a more or less flat plane at a depth of approximately 140 m below mean sea level. The leaching surface displays a certain relief with depressions in some places with a proved maximum of app. 175 m below mean sea level. The overlying cap rock has a very low hydraulic conductivity and isolates the salt structure from the aquifer system in the overlying upper Cretaceous rocks.

Recently active brine inflows into the mine openings have been low. Thus, one location is situated far from the disposal areas in the Marie mine (potash seam H) and has an inflow rate of about 10 m³/a. A dropping location with an inflow rate of about 1 m³/a is situated on the first level of the central part in the Bartensleben mine, close to the main anhydrite. The chemical composition of the NaCl-saturated, Mg-rich solutions have been nearly constant and prove a contact with potash salts.

Regarding potential future pathways special attention has to be paid to the main anhydrite (z3HA) and the overlain potash seam C. These geological units connect the cap rock to the excavation disturbed zone of the mine openings of the central part and may act as future pathways for fluids (Fig. 1).

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**Fig. 1.** Host rock, mine openings and potential pathway of fluids
CLOSURE CONCEPT

A closure concept has been established which is based on a comprehensive backfilling of the excavations with a hydraulically transported salt concrete (mixture M2 and M3 (1)). The function of the backfill is to stabilize cavities as well as to reduce the mine’s openings’ volume and to seal single cavities or groups of cavities containing radioactive waste. Stabilization measures are necessary to protect the ground surface and to avoid the evolution of pathways induced by mechanical failure of the rock salt barrier around the disposal areas, which is intact, actually (2,3). Limitation of leaching processes by volume reducing backfilling measures is required for stability reasons as well as to conserve the geometric structure of the mine globally. Thus, the connection and interaction of mining excavations and potential pathways remain fixed serving as initial and boundary conditions for the long-term safety proof.

Taking into account the stabilizing and leaching limiting function of the backfill the remarkable safety relevant property of the ERAM, i.e. the intact geological rock salt barrier surrounding the disposal areas, will be conserved. Thus, the man-made access drifts are the only relevant potential pathways for radionuclide release from the disposal areas. Thus, their sealing is of major importance.

DRIFT SEALS

Position of drift seals

The closure concept requires the erection of 26 drift seals at different levels in the Bartensleben mine. As they separate the disposal areas from the residual mine the positions of the drift seals are defined by the geometric structure of the mine as well as by the geological structure, because the drift seals preferably have to be placed in rock salt layers to avoid leaching processes locally. In case of unsaturated brine inflow first NaCl-saturation can be expected. These solutions will be enriched owing to the reactions of potash seams with Mg-sulfates and -chlorides while halite will be precipitated (4). Due to the crushed salt ingredient of salt concretes as well as to the low brine intrusion rate of 11 m³/a at present and 600 m³/a estimated to be the maximum in future no NaCl unsaturated brine will be available close to the seals. Thus, no further pathway will be created by dissolution of the rock salt barrier in the vicinity of the drift seals, e.g. in the excavation disturbed zone (EDZ).

Fig. 2, for example, shows the drift seals placed between potash seams B (southern field, disposal area) and C (central part, potential pathway) on the 2nd level separating the southern field from the central part. The drift seal in the northern ventilation drift on the 2nd level is the most severe location, as the thickness of the intact rock salt layer between potash seams B and C is only about 25 m. Thus, the drift seal’s length is short. In addition, potash seams B and C were excavated extensively in the past, cf. Fig. 2. For this reason access to the drift seal’s position is complicated.
Design of drift seals

Basic requirements on the drift seals arise from the long-term safety analysis as well as from restricted length and limited access. To assure agreement with the radiological long-term safety objectives a permeability of the drift seals less than $10^{-16}$ m$^2$ to $10^{-18}$ m$^2$ is required on average. Restricted length of drift seals leads to a design, providing the drift seals serve as both seal and abutment to achieve a maximum of hydraulic resistance. Due to limited access the construction has to be simple.

Every drift seal consists of segments made of salt concrete M2. Each segment is 25 ±5 m long, several of them may be arranged one behind the other in order to meet the requirements. At minimum a drift seal consists of one segment, e.g. the drift seal in the northern ventilation drift (Fig.2). The length of segments is restricted to reduce the impact from geological movements as well as restraint stresses due to the heat of hydration. To assess the influence of geological movements the dimensions of small anhydrite blocks in the ERAM were used as a site specific natural analogue.

The segments are separated from each other by plastic joints containing salt material, e.g. salt briquettes or crushed salt (Fig.3). Prior to the construction of the segments the EDZ along the drift wall will be removed. After construction of the sealing body cement grout is injected into the contact zone between the sealing body and the surrounding rocks using sealing rings connected to the pump (forward/backward run) by a hull for sealing ring tubes, which will be over-
drilled after having completed the injection process. The borehole itself will be backfilled by salt concrete M2 afterwards. Thus, each segment is provided with a ring seal and is pre-stressed sufficiently to withstand the load of future fluid pressure. The whole structure fulfills the requirement to serve as a seal and as an abutment. By this force-transferring design relative sliding between the sealing body and the surrounding rocks is excluded and the tightness of the contact zone is guaranteed.

**HYDRAULIC RESISTANCE OF DRIFT SEALS**

Regarding hydraulic resistance the drift seals consist of three main elements, the sealing body, the contact zone between sealing body and surrounding rock salt and the excavation disturbed zone (EDZ). Additionally, it has to be observed that permeability may increase due to crack evolution caused by hydration heat during the construction phase or by mechanical loads. Safety evidence criteria to exclude mechanical failure and crack evolution are already described in (5).

Brine migration through salt concrete might degrade the hydraulic behaviour of the seal due to chemical reactions, however. This could not be avoided because no material has been known that is chemically stable to all possible brines getting into contact with the seals. The chemical constitution of the brine depends on its flow path and could not be pre-determined in detail due to the geometrical complexity of the mine and the salt structure.
Laboratory experiments and model calculations indicate that the hydraulic conductivity of a seal will increase depending on the amount and chemical constitution of the brine migrating through it. Penetration of the seals starts when a significant hydraulic gradient has established between the disposal areas and the remaining part of the mine. Assuming an initial permeability of less than $10^{-18}$ m$^2$ model calculations based on laboratory experiments show that in the worst case constitution of the brine the seals will keep their function for at least some 5,000 years (6) after having got in contact with that brine. The degradation of the drift seals has been taken into account in the safety analysis and has been shown to be tolerable. Thus, the initial permeability of $10^{-18}$ m$^2$ became the substitute safety evidence criterion to assess the drift seals independently in the context of the long-term safety proof.

**Excavation disturbed zone**

The permeability of the excavation disturbed zone (EDZ) has been measured at selected points in the ERAM. Measured values lie within a range of $5 \cdot 10^{-17}$ m$^2$ to $1 \cdot 10^{-20}$ m$^2$ in trimmed drifts, i.e. within common values for EDZs in salt mines (7). As the EDZ will be removed before constructing the seals, there is sufficient knowledge available on the EDZ at present. This aspect will be considered again when the drift seal’s construction is impending.

**Sealing body**

The sealing body will be made of salt concrete M2. The composition of salt concrete M2 consists of 16.4 wt% cement and fly ash, 13.4 wt% water and 53.8 wt% crushed salt, i.e. 328 kg/m$^3$ cement, 328 kg/m$^3$ fly ash 267 kg/m$^3$ water, 1072 kg/m$^3$ crushed salt (grain size 0-2mm).

The total porosity of salt concrete M2 is 18.1 v%, the porosity that could be measured by porosimetry methods was 14.2 v%. Additional data turning out from hydraulic laboratory tests of salt concrete M2 (8) are given in Tab. I. The data show a very high hydraulic resistance and they agree with the fact that the pore radius of salt concrete M2 is less than 20 nm (9). If the pore space is filled with brine, salt concrete M2 is practically impermeable taking into account the boundary conditions of the ERAM. An upper bound of the Lithium ion diffusion coefficient was measured to be less than $1 \cdot 10^{-14}$ m$^2$/s, being the measuring range of the experimental equipment. Lithium ions were used because of their property not to react with salt concrete.

All results of laboratory tests indicate that salt concrete material is less permeable to brine than standard so-called water impermeable concrete, whose permeability (mean value) was determined to be $10^{-19}$ m$^2$ (10). Thus, the permeability of the sealing body is mainly a question of quality assurance measures and rating the quality that will achieved in situ, correctly.

Due to the results of laboratory tests actually it is proceeded on the assumption that the permeability of the sealing body will be in compliance with the required value of $10^{-18}$ m$^2$. 
Table I: Results of hydraulic laboratory tests on salt concrete M2 samples

<table>
<thead>
<tr>
<th>storage conditions</th>
<th>confining pressure [MPa]</th>
<th>axial fluid pressure [MPa]</th>
<th>medium</th>
<th>permeability [m²]</th>
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</thead>
<tbody>
<tr>
<td>temperature[°C]</td>
<td>relative humidity [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20/65</td>
<td>2.5 –10.0</td>
<td>1.34 – 5.6</td>
<td>gas</td>
<td>5.8<em>10⁻²⁰ – 5.3</em>10⁻²¹</td>
</tr>
<tr>
<td>dried samples</td>
<td>1.0 – 10.0</td>
<td>0.56 – 9.0</td>
<td>gas</td>
<td>5.4*10⁻¹⁸ – 1.0 * 10⁻¹⁸</td>
</tr>
<tr>
<td>20/65</td>
<td>2.5</td>
<td>1.8</td>
<td>gas</td>
<td>6.1*10⁻²⁰ – 1.5 *10⁻²⁰</td>
</tr>
<tr>
<td>pore space saturated</td>
<td>2.5</td>
<td>1.8</td>
<td>Q-brine</td>
<td>≤ 3.0*10⁻²³ (measuring range)</td>
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<tr>
<td>pore space saturated</td>
<td>2.5</td>
<td>1.8</td>
<td>NaCl-brine</td>
<td>≤ 6.0*10⁻²⁴ (measuring range)</td>
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<tr>
<td>pore space saturated</td>
<td>2.5</td>
<td>2.1</td>
<td>gas</td>
<td>no gas intrusion measured</td>
</tr>
<tr>
<td>pore space saturated</td>
<td>8.0</td>
<td>7.0</td>
<td>gas</td>
<td>no gas intrusion measured</td>
</tr>
</tbody>
</table>

SPECIAL PROBLEM: CONTACT ZONE

According to German technical regulations in civil engineering (10) investigations on comparable structures are necessary for assessing the hydraulic resistance of contact zones. Data to rate the contact zone between salt concrete sealing body and EDZ are not available yet. To gain a reliable data basis in situ tests are planned in the Asse salt mine investigating the contact zone of a 10-year-old salt concrete seal by permeability tests, hydraulic fracturing and ultrasonic fault analysis. Finally, core samples from the Asse seal, the contact zone and the surrounding rock salt will be examined by laboratory tests, to get better knowledge on the quality of salt concrete achieved in situ and its adhesion to the rock salt contour.

The composition of the salt concrete used for constructing the Asse seal was approx. 17.9 wt.% cement, 70.5 wt% crushed salt (maximum grain size 16 mm), 11.6 wt% NaCl saturated brine. This mixture is equivalent to a composition of 380 kg/m³ cement, 182 kg/m³ water and 1560 kg/m³ salt ingredients. Due to handling and expected permeability the newly developed M2 has been improved in comparison to the salt concrete used for the Asse seal. When the Asse seal was designed it was planned to erect different components serving as a seal and an abutment. The salt concrete plug was looked upon to serve primarily as an abutment and secondarily as a seal. However, hydraulic bond tests investigating borehole seals consisting of different salt concrete mixtures performed prior to the construction of the Asse seal already showed, that the salt concrete composition is of minor influence to the hydraulic resistance in comparison to the contact zone and the surrounding EDZ. To obtain data on the hydraulic resistance of the contact zone the Asse seal is looked upon as a comparable structure to the ERAM seals in compliance with the technical regulations (10).

The following investigations will be performed at the Asse seal.
**Permeability tests**

In situ permeability tests are planned to rate the permeability in the contact zone. The position of boreholes for permeability tests is given in Fig. 4. Prior to the permeability tests the borehole will be inspected by borehole camera visualization and endoscopy. As the degree of pore space saturation as well as the magnitude of a potential pore pressure is not known 10 years after having erected the seal, it is intended to perform permeability tests using both gas and liquids. Additionally, it is not known whether the contact zone behaves more like a porous or a fractured medium. For this reason special test sequences are planned taking into account both cases.

![Fig. 4. Overview of boreholes planned for investigation of the Asse seal (blue: permeability tests/hydraulic fracturing, pink: ultrasonic fault analysis)](image)

**Hydraulic fracturing tests**

Hydraulic fracturing tests will be performed to investigate whether the contact zone is really the weakest interface after having been subject to rock pressure for 10 years. Thus, in addition to the minimum stress component in the contact zone the direction of the minimum stress component will be evaluated. The direction of the minimum stress component will be compared to the direction of the contact zone. After having carried out the permeability measurements the hydraulic fracturing tests will be performed using the same boreholes for testing.
Ultrasonic fault analysis

The number and extension of faults and defects in situ are of major interest to rate the resistance of a structure against corrosion. If there are only isolated faults corrosion will proceed slowly because of self-buffering. However, if there is a network of faults, corrosion processes will be accelerated leading to an earlier degradation of the seal. Ultrasonic fault analysis is an accepted method to detect faults and defects giving the data basis to rate whether they are isolated faults and defects or whether they are connected forming a hydraulic network. Further, in case there exist only isolated faults and defects a data basis will be gained by ultrasonic fault analysis to rate the effective length of the hydraulic resistance of the seal as required in the technical regulations.

Laboratory tests

From the salt body of the Asse seal, the contact zone and the surrounding rock core samples will be extracted to perform laboratory tests. Standard laboratory tests will be carried out to determine the mechanical and hydraulic properties. Additionally, pore volume, density and separation planes will be examined. By mercury porosimetry methods the pore radius and pore distribution will be investigated. Recrystallisation and differences in texture will be analysed using thin sections.

CONCLUSION

The hydraulic resistance of the drift seal is determined by three elements, the EDZ, the sealing body and the contact zone between sealing body and surrounding rock salt. While a reliable data basis is available to assess the hydraulic resistance of the EDZ and the sealing body, the data basis to rate the contact zone is unsatisfactory. To overcome this problem investigations will be performed at a comparable seal as required by technical regulations. Permeability tests, hydraulic fracturing tests and an ultrasonic fault analysis will be performed in situ. Additionally, a laboratory program is set up using core samples from the Asse seal.

If a permeability of the contact zone of less than \(10^{-18}\, \text{m}^2\) is determined in situ, the data basis to prove the sufficient hydraulic resistance of drift seals is available. In this case the corrosion process in the contact zone is sufficiently slow and long-term stability of the contact zone is guaranteed during the required time period.

Thus, the safety relevant documents for the drift seals in the context of the long-term safety proof for the ERAM will be prepared.

REFERENCES

4. G. EILERS et al., “Post closure safety of the Morsleben repository, Germany”, Summer Course on Geology and Mineralogy of Radioactive Waste Repositories, 2002, Freiburg University, Germany (to appear)