

POST CLOSURE SAFETY OF THE MORSLEBEN REPOSITORY

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ABSTRACT

After the completion of detailed studies of the suitability the twin-mine Bartensleben-Marie, situated in the Federal State of Saxony-Anhalt (Germany), was chosen in 1970 for the disposal of low and medium level radioactive waste. The waste emplacement started in 1978 in rock cavities at the mine's fourth level, some 500 m below the surface. Until the end of the operational phase in 1998 in total about 36,800 m³ of radioactive waste was disposed of.

The Morsleben LLW/ILW repository (ERAM) is now under licensing for closure. After completing the licensing procedure the repository will be sealed and backfilled to exclude any undue future impact onto man or the environment. The main safety objective is to protect the biosphere from the harmful effects of the disposed radionuclides. Furthermore, classical or conventional requirements call for ruling out or minimizing other unfavourable environmental effects. The ERAM is an abandoned rock salt and potash mine. As a consequence it has a big void volume, however small parts of the cavities are backfilled with crushed salt rocks. Other goals of the closure concept are therefore a long-term stabilization of the cavities to prevent a dipping or buckling of the ground surface. In addition, groundwater protection shall be assured.

For the sealing of the repository a closure concept was developed to ensure compliance with the safety protection objectives. The concept anticipates the backfilling of the cavities with hydraulically setting backfill materials (salt concretes). The reduction of the remaining void volume in the mine causes in the case of brine intrusions a limitation of the leaching processes of the exposed potash seams. However, during the setting process the hydration heat of the concrete will lead to an increase of the temperature and hence to thermally induced stresses of the concrete and the surrounding rocks. Therefore, the influence of these stresses and deformations on the stability of the salt body and the integrity of the geological barrier was examined by 2D and 3D thermo-mechanical computations. The compliance of the safety objectives are proved on the basis of safety evidence criteria. It can be concluded that the closure concept is able to serve all conventional and radiological safety objectives.

INTRODUCTION

In the former German Democratic Republic (East Germany) the abandoned salt mine Bartensleben was selected to serve as a repository for low and intermediate level (LLW, ILW) radioactive wastes. Located near the village of Morsleben in the Federal State Saxony-Anhalt this mine was named the "Repository for Radioactive Waste Morsleben (ERAM)". The decision to establish the repository was based on safety and technical-economic studies performed in the 1960s. It was designed, constructed and commissioned during 1972-1978. Following studies and the successful demonstration of the disposal technologies used a first operational license was granted in 1981.

After German reunification (October 3, 1990) the Federal Government of Germany took over the responsibility for the repository. It is represented by the Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS) which is entrusted by the Federal Minister of Environment, Nature Conservation and Reaktor Safety (BMU). The DBE became then, on behalf of the BfS, the repository operator. The final disposal of waste was stopped in 1998. Under contract of the BfS the backfilling and closure of the Morsleben repository is being planned presently.

REPOSITORY SITUATION AND BOUNDARY CONDITIONS

The ERAM is a twin-mine consisting of the mine concessions Marie and Bartensleben which are connected by drifts on the first level (-253 m below sea level) and on the third level (-332 m below sea level). The ERAM is developed by two shafts. The shaft "Bartensleben" is the main shaft used for men ride and waste transport. Approximately 1.6 km north-west of the Bartensleben shaft is located the auxiliary shaft Marie. The shafts provide access to a widespread system of drifts, cavities and blind shafts between 320 m and 630 m below the earth surface. The 525 m deep shaft Bartensleben connects four main floors (second level -291 m below sea level, fourth level -372 m below sea level) and the 520 m deep shaft Marie connects two main floors.

The twin-mine extends from the north-west to the south-east over a length of 5.5 km and crosswise over 1.4 km at maximum. Before the beginning of the disposal of radioactive waste rock salt and potash mining (carnallite, kieseritic hartsalz) went on for several decades at the site. Thus, most of the mine openings are excavated according to the mining or production activities that means the occurrence of valuable raw salts. The cavities made by chamber working have dimensions of up to 100 m in length and 30 m in width and in height. Especially the central part of the Bartensleben mine is marked by extensive mining activities on the main and sublevels. The total volume of the mine is about 6 million m³. Figure 1 shows a map with the outline of the ERAM and Figure 2 a schematic overview of the underground excavations.

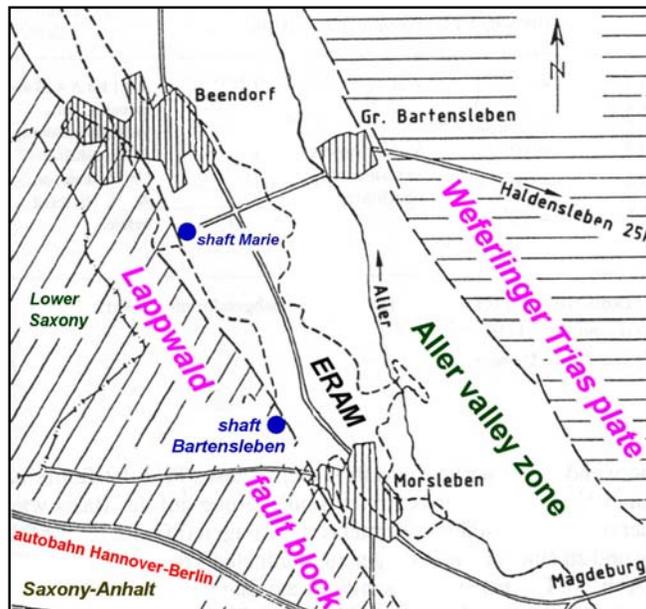


Fig. 1. Outline of the repository for radioactive waste Morsleben near the border of the Federal States Lower Saxony and Saxony-Anhalt. The twin-mine extends from the north-west to the south-east over a length of 5.5 km. The maximum extension of the underground excavations is in south-west to the north-east direction about 1.4 km. Concerning the geological structures “Lappwald fault block”, “Aller valley zone”, and “Weferlinger Trias plate” see the following text.

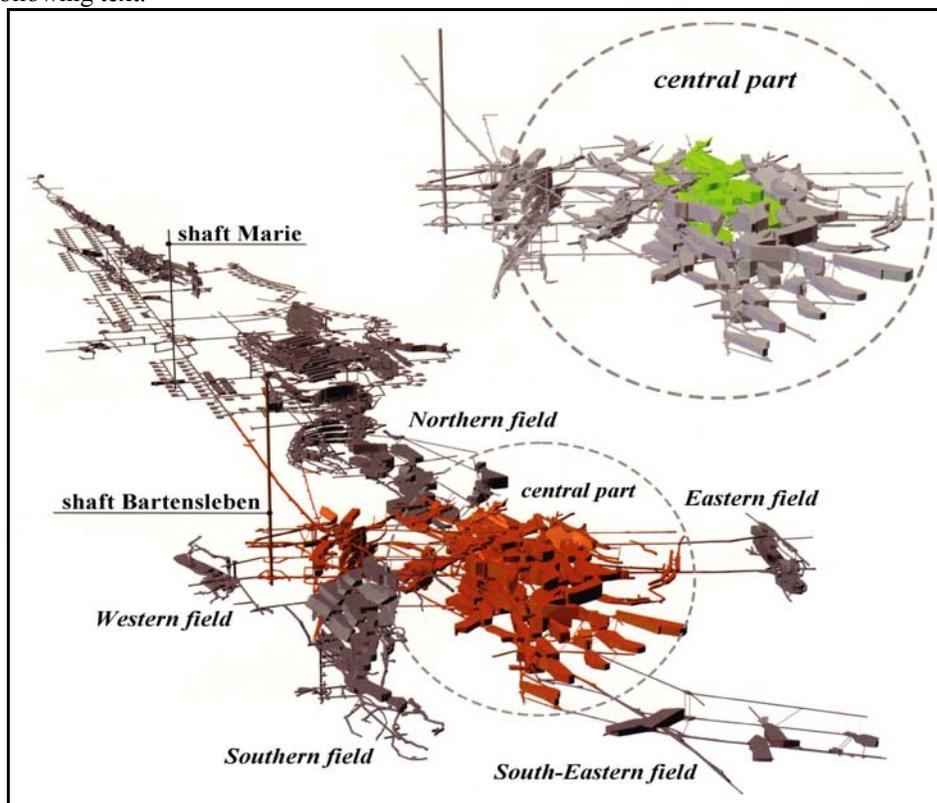


Fig. 2. Overview of the twin-mine Marie-Bartensleben (Repository for Radioactive Waste Morsleben, ERAM). The distance between the two shafts is about 1.6 km. The depths of the shafts is 525 m (Bartensleben) and 520 m (Marie).

The ERAM is located in an uplift salt structure of the SE-NW trending Aller valley zone (Allertal zone), named after the small river Aller. The Aller valley zone covers an area of approximately 50 km². It is marked by the Lappwald fault block in the SW and by the Weferlinger Trias plate in the NE. At the site the top of the salt plug is at -140 m below sea level and the total thickness of the salt body varies between 380 and 580 m. The salts belong to the Upper Permian Zechstein strata. A characteristic of the salt body is an intensive folding of the salt layers and a high amount of anhydrite rocks ("Hauptanhydrit"). The anhydrite blocks are geo-mechanically stabilizing the salt plug and thus lead to a low convergence of the underground excavations. The salt structure is isolated from the aquifer system in Upper Cretaceous rocks by a thick gypsum (residual) cap rock, which has a very low hydraulic conductivity. The aquifer is overlain by loose or semiconsolidated glacial sediments, such as tills.

Radioactive waste with negligible heat generation (predominantly short-lived radionuclides) was disposed of in the Bartensleben mine only. The wastes originate from the operation of nuclear power plants, decommissioning, and applications of radionuclides in research, industry, and medicine. Solid and liquid wastes and sealed emitters has been emplaced. Cemented waste forms represent a significant part of the solid inventory. Most of the wastes are disposed of in the western, southern and eastern mining areas called "Westfeld", "Südfeld" and "Ostfeld", respectively. In addition, low amounts of waste are emplaced in the central part ("Zentralteil") and the northern field ("Nordfeld") of the Bartensleben mine (see Figure 1). The wastes are stored in the mine structures on the 4th level (-500 m level) and in openings of the 5a level. Drum piling and dumping, as well as stacking of drums and cylindrical concrete containers are the used disposal technologies of solid wastes. The liquid waste was mixed underground with hydraulic binders, pumped into the storage cavity and allowed to solidify there (1978-1990). Until the end of the operational phase a waste volume of about 36,800 m³ has been disposed of (approximately 28,500 m³ of solid waste and 8,300 m³ of liquid waste). In Table I the emplaced waste volumes and activities are summarized according to the mining fields of the ERAM.

Table I. Volume and activities of the disposed radioactive wastes in the Repository for Radioactive Waste Morsleben (ERAM).

Emplacement area	Waste volume [m ³]	Activities [Bq]
Western field	18,637	2.3·10 ¹³
Southern field	10,119	8.2·10 ¹³
Eastern field	6,139	1.1·10 ¹³
Northern field/central part	1,858	4.1·10 ¹²

During the post-closure phase only negligible quantities of intruding brines into the repository should be able to migrate to the biosphere. Hence, the potential flow routes of fluids are investigated in detail. Recently the brine inflows into the mine are very low. One brine occurrence is sited in the "Lager H" of the Marie mine. About 10 m³ of Mg-rich salt solution is flowing into the chamber every year. The location is sealed from the main galleries by an old dam construction, however, the quality (stability) of the dam is hardly to evaluate. Another brine

occurrence with a flow rate of approximately 1 m³/a is situated in the central part of the Bartensleben mine. In this case a connection to the groundwater system can be excluded.

With respect to the geological and geo-mechanical situation and due to the mining of salts an inflow of brines into the repository in the post-closure phase can not be excluded absolutely. In particular locations that must be taken into consideration consist of enclaves of competent rocks with a tendency for brittle fracture, such as anhydrite blocks (“Hauptanhydrit”) or potash seams in the vicinity of the salt table or with a contact to the salt boundary. However, an important fact is that the active brine influxes and the potential flow routes are situated in areas, where only small amounts of wastes are disposed of. In contrast, the integrity of the geological barrier impede brine influxes into the emplacement areas.

The following aspects are of special importance for the backfilling and closure concept:

- The mining of salts results in a big volume of the underground openings (high excavation rate). Only small amounts of crushed rock salts are used as backfilling material.
- Brine influxes and potential pathways for brines exist (anhydritic rocks, potash seams) only in areas of the mine, where negligible amounts of radioactive wastes are disposed of.
- Nearly all wastes are disposed of in emplacement areas which are surrounded by impermeable rock salts. Thus, during the post-closure phase brine migrations through the rock salt barrier can be excluded.

CLOSURE CONCEPT

With respect to the three main characteristics of the repository mentioned before a closure concept was developed. The goals of the concept are the long-term stabilization of the cavities (the high excavation rate does not bear any risk for the geo-mechanical stability of the mine for the next decades), the limitation of leaching processes of potash seams by reducing the void volume and the sealing of the emplacement structures containing the radioactive waste by technical barriers. For the stabilization of the mine the backfilling of distinct cavities is necessary, e.g. in the highly mined central part Bartensleben. Concerning the reduction of the mine openings generalized requirements are available with respect to different parts of mining fields. In general the backfill requirements arising from stabilization purpose are the decisive factor and the requirements arising from the limitation of leaching processes are fulfilled automatically. To separate the emplacement structures from other parts of the mine 25 sealings of different cross-sections and lengths up to several hundred meters on the mining levels are needed.

For the backfilling and as a sealing material different salt concretes are provided, called M2 and M3. The mixing of the components of the concretes will be performed above ground. It is planned to pump the suspension via tubes through the shaft and drifts and to stow the fresh concrete via drilling holes into the underground openings. The only difference of M2 and M3 is the quantity of their components. The components itself are identical. The composition of the variants however is strongly influencing the material properties of the concretes serving the

different quality requirements. For example, the variant M2 produces in comparison to the mixture M3 a higher amount of hydration heat as a result of the more highly cement content. The composition of the mixtures M2 and M3 are given in Table II (1,2). The cement (high sulfate resistant) and the coal fly ash are building materials according to the German industrial standards (DIN). The maximum grain size of the crushed rock salt is 20 mm. The water content guarantees a transport of the suspension over long distances.

Table II. Recipe of salt concretes M2 and M3.

Components	M2		M3	
	kg/m ³	wt. %	kg/m ³	wt. %
Cement	328	16.4	197	9.9
Coal Fly Ash	328	16.4	459	23.0
Water	267	13.4	252	12.6
Crushed rock salt	1,072	53.8	1,087	54.5

The advantage of the use of hydraulically setting concrete materials is a stabilization effect in a relatively short time. The water needed for the hydraulic transport is fixed in the crystal structure of the hydration products and the pore volume of the concretes. Thus, no retransportation of contaminated water into the biosphere is to be feared. In addition, there will not exist a significant amount of free water or brine resulting from the backfilling process in the emplacement cavities leading to a dissolution of radionuclides and as a consequence to a release of radionuclides at an early point of time, although the brine inflow rate itself into the mine is small. Not to forget to mention the saturation capacity of the salt component in the concrete (about 54 wt.%). It is of major importance with respect to the avoidance of leaching processes in the disturbed rock zone (excavation damage zone, EDZ) at the position of sealing constructions. Unsaturated brines may cause an increase of the permeability and therefore a reduction of the efficiency of the sealings.

According to the closure concept it has to be taken into account that cement based concretes are developing hydration energy or heat leading to a temperature rise in the concrete and the surrounding salt rocks. The hydration heat causes thermo-mechanical induced stresses which may result in the formation of fractures. Thus, the selected salt concretes contain a high amount of fly ash, whereas the proportion of cement is limited. However, in the case of huge cavities the hydration heat may not be neglected. The increase of the temperature during the hydration process of the salt concretes was determined under adiabatic conditions at different start temperatures of the mixtures. In addition, these measurements were used for the calculation of the activation energy (E_A) according to the Arrhenius relationship.

PLAN OF BACKFILLING

According to main characteristics of the mine every single cavity and mining excavation was assigned to a backfilling category. In total four categories can be subdivided:

- Backfilling category I includes all cavities and mining excavations that must be sealed. For backfilling category I a high backfilling quality must be achieved. The averaged permeability of a cross section must be equal or less than 10^{-16} m².
- Backfilling category II includes all cavities and mining excavations that must be backfilled by nearly 100 % (more than 95 %) by stability reasons or because they may develop an mining induced pathway for water and brine.
- Backfilling category III includes all cavities not belonging to category I, II or IV. The requirement for this category is averaged backfill standard of 65 % per mining field for the reason of limiting leaching processes.
- Backfilling category IV includes all excavated carnallite layers, which are mostly inaccessible. An backfill standard of more than 90 % should be reached, but can not be verified. For this reason only a degree of backfilling of 50 % is included in the safety analysis.

SAFETY OBJECTIVES

The main safety objective is to protect the biosphere from harmful effects of the disposed radioactive waste. Additionally, conventional safety objectives arising from the Federal Mining Act (3) and the Water Protection Act (4) must be taken into account. Protection of the ground surface and the groundwater has to be regarded. As the Morsleben repository is a large, former salt mine with huge cavities, the conventional protection objectives become essential. Following items must be proved in detail:

- (1) Limited subsidence of the ground surface (conventional safety objective)
- (2) Conservation of a permeation barrier of adequate thickness without risk of brine intrusion at present for cavities (radiation protection)
- (3) Mitigation of fissure evolution by leaching processes (radiation protection)
- (4) Maintaining a “sufficient” hydraulical and chemical barrier-system leading to retardation of radionuclides within available pathways (radiation protection)
- (5) Occupational health and safety during the backfilling process (workers protection, radiation protection)
- (6) Guaranteeing groundwater protection (conventional safety objective)

Recent and expected brine inflow rates are very low. Starting the prospective evolution that means the occurrence or the absence of brine intrusions, of the repository a dry and a wet repository situation (dry/wet scenario) must be subdivided. In the case that the mine remains dry the radiation and the conventional groundwater protection goal are fulfilled automatically, however, the protection of the ground surface has to be shown. In contrast, in the case of a wet repository (filled with salt solutions) the compliance with the radiation and the groundwater protection rules has to be shown. The proof of the ground surface's protection, however, is less difficult in comparison with a dry repository, because the brine pressure decreases the convergence rate of the cavities and as a consequence the sinking rate of the ground surface. This

effect is traditionally used to stabilize abandoned salt mines. In the following the safety evidence criteria are summarized and quantified. In addition, the safety analysis methods and safety measures are described.

SAFETY EVIDENCE CRITERIA

Concerning the protection of the ground surface (*safety objective 1*) two safety evidence criteria are formulated quantitatively. They are in accordance with the German regulations (e.g. Federal Mining Act). The first criterion is based on the maximum subsidence of the ground subsurface. The limiting value is 1 m. In this case no Environmental Impact Assessment is necessary. Due to salt creep and the convergence of underground excavations it is not excluded that a subsidence of 1 m is exceeded over a long time. For this reason a second criterion was derived, which can be applied alternatively. The inclination rate of the ground surface is limited to 1/300 per 100 years. Inclination rates of this magnitude are causing only very small damages on buildings that are comparable to usual building wear in 100 years (5,6). These damages will be eliminated in the context of usual buildings redevelopment.

To show that the *safety objective (2)* is achieved it is essential to make a distinction between mining excavations that are affected, that might be affected in the future or that will never be effected by brine intrusion because of massive protective geological layers. In the case of the Morsleben repository all mining excavations, whose distance to the salt table is more than 130 m are outside of the brine intrusion danger area. Mining excavations whose minimum distance to the salt table is 60 m and 25 m to anhydrite and carnallite layers, respectively, are also outside of brine intrusion danger area, even there is a connection of the anhydrite or carnallite layer to the overburden.

Concerning mining excavations that might be affected by a brine inrush a distinction is made between excavations whose EDZ can be the reason for a potential brine intrusion in the future and excavations with an unfavourable geologic situation. Due to the plastic behaviour and the healing capacity of the rock salt it is shown for cavities with a EDZ, that the geo-mechanical situation will improve in the future. The *dilatancy criterion (7)* and the *fluid criterion* according Eq. (1) and Eq. (2) are used as quantitative measures to specify this improvement.

$$\text{dilatancy criterion} \quad \frac{\tau}{\sigma_*} \geq -0,01679 \cdot \left(\frac{\sigma^2}{\sigma_*} \right) + 0,8996 \cdot \frac{\sigma}{\sigma_*} \quad (\text{Eq. 1})$$

with

$$\text{octahedral shear stress:} \quad \tau = \frac{1}{3} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad [\text{MPa}]$$

$$\text{mean stress :} \quad \sigma = \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) \quad [\text{MPa}]$$

$$\text{normalization:} \quad \sigma_* = 1 \quad [\text{MPa}]$$

$$\text{fluid criterion} \quad \sigma_1 > p \quad (\text{Eq. 2})$$

with minor principal stress: σ_1

depth-depending brine pressure: p ($p = 0,012655 \text{ MPa/m} \cdot z_T$; z_T : depth below surface)

As there is no brine intrusion at present the probability of brine inflows will be reduced if the integrity of the salt barrier is improving. Mining excavations with an unfavourable geologic situation and locations with existing brine inflows are recognized as potential or existing pathways. They are treated in the long-term safety analysis.

As salt concretes are used for the backfilling of the mine, the hydration heat must be regarded. To make sure that an increase of the temperature will not accelerate leaching processes at the salt table, which would result in an acceleration of the subsrosion processes (subsurface solution of salt), a temperature limit was derived. The maximum temperature rise permitted at the salt table is 1 K. Measurements in the mine identified this temperature rise being within the range of site specific natural temperature variations caused by recrystallization processes. Thus, an increase of 1 K do not accelerate any leaching processes. Special emphasis was layed on the integrity of the anhydrite blocks embedded in the rock salt, which may act as a potential pathway of fluids. In this case the temperature rise is limited by 2 K. In-situ observations and laboratory tests showed that such an increase of the temperature did not impact the stability of the anhydrite blocks.

Safety objective (3) is not understood to avoid any kind of fissure evolution by leaching processes, however leaching processes must be avoided creating pathways between emplacement structures and other parts of the mine. This objective is fulfilled by constructing sealings (drift seals) at certain positions in the mine. They are evaluated in such a way that no unfavourable geological layers (potash seams, anhydrite layers) are connecting the emplacement areas with the residual mine. Thus, leaching processes are only of interest in the near field of the sealings, e.g. in the EDZ of the drifts, which are sealed. Leaching processes can be avoided if the brine is saturated. Consequently, the safety evidence criterion for avoiding relevant leaching processes bases on the saturation conditions of the brines.

The safety evidence criterion related to *safety objective (4)* is a kind of secondary criterion derived from the long-term safety analysis regarding the settings of the German radiation protection regulations (8). The long-term safety analysis has proved (9) that the radiation protection safety objective is fulfilled (limit 0,3 mSv), if the averaged cross section permeability $k=10^{-16} \text{ m}^2$ of the sealings is not exceeded.

Safety objective (5) can be separated in classical mining occupational health and safety, safety in handling the backfill material and radiological safety concerning pumping contaminated water during the backfill process. It is fulfilled by technical and administration measures. Thus, the emplacement fields will be closed by technical measures, e.g. walls.

A measure to ensure *safety objective (6)* is derived by recalculation of aggressive substance transport into aquifers quantifying permissible substance concentrations in eluats. The

permissible aggressive substance concentrations consider the regulations of the Water Protection Act (4).

SAFETY PROOFS AND SAFETY MEASURES

Concerning *safety objective (1)* 3D and 2D numerical calculations showed (10,11) that the safety evidence criteria are fulfilled in the case of the dry and the wet repository situation. Both cases had to be considered as the stabilization effect of the brine is missing in cavities, which are backfilled in parts in the case of a dry repository. On the other hand cementitious materials are corroded in dependence of the permeability by Mg-rich brines. The chemical reactions cause a loosing of the material strength over a long period of time. In the case of the ERAM the chemical composition of the brines is difficult to predict, because of the backfilling of openings, the complicated internal structure of the diapir and the chemical reactions of the salt solutions with the concrete, which may result in an increase of the pH-value and therefore a precipitation of Mg-bearing phases. However, after long reaction times a Mg-rich solution can be assumed. It was shown that limited subsidence of ground surface is achieved already by the brine pressure without taking into account the stiffness of the corroded concrete. Thus, it was not necessary to develop requirements on the properties of the corroded backfill. In the framework of the investigation of the wet repository situation the dissolution of the most unfavourable carnallite layers close to ground surface was assumed as well as the dissolution of rock salt in the most unfavourable subsrosion zone. The results of the calculations are given in Table III.

Table III. Maximum subsidence and inclination rate of the ground surface under wet repository conditions.

Years after closure	Maximum subsidence [m]	Maximum inclination rate [mm/a]
4,000	0.42	0.2
5,000	0.47	0.1
10,000	0.70	< 0.1

Due to the influence of massive pillars at orthogonal angles to the lateral direction of the cavities a 3D-calculation was necessary considering the dry repository situation. In the case of the wet repository a 2D-calculation was sufficient as the brine pressure reduces the influence of the pillars. A typical 3D model for one part of the repository is given in Figure 3.

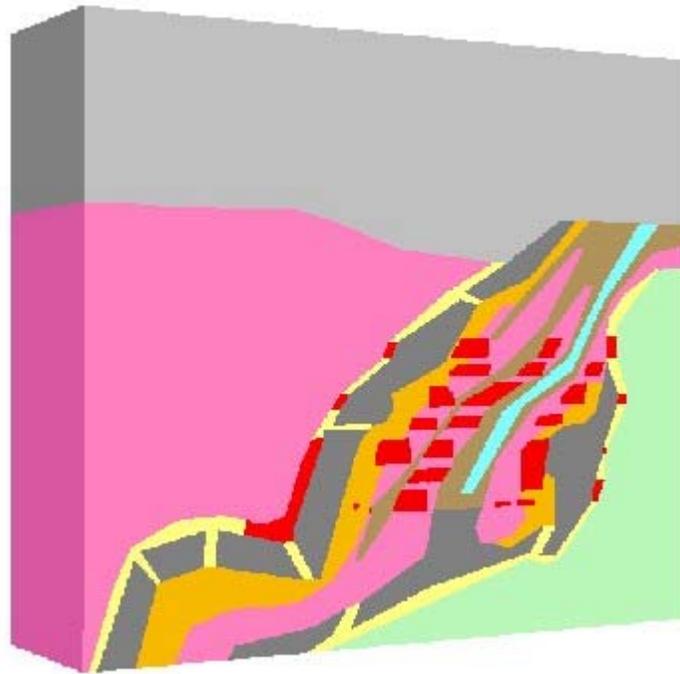


Fig. 3. Numerical 3D model of the ERAM (central part, Bartensleben) with indication of geological layers and underground chambers. The red areas mark excavations and the grey field the overlying strata (cap rock, overburden). The geological structure of the diapir is modeled depending on the creep behaviour of the rocks.

The proof of conservation of permeation barrier (*safety objective 2*) for mining excavations not situated in the brine intrusion danger area is automatically available. The geo-mechanical improvement of the salt barrier bounding other cavities as the result of backfilling is shown by numerical calculations. Figure 4 illustrates the results of an evaluation of the *dilatancy criterion* (Eq. 1) before and after backfilling of the underground excavations.

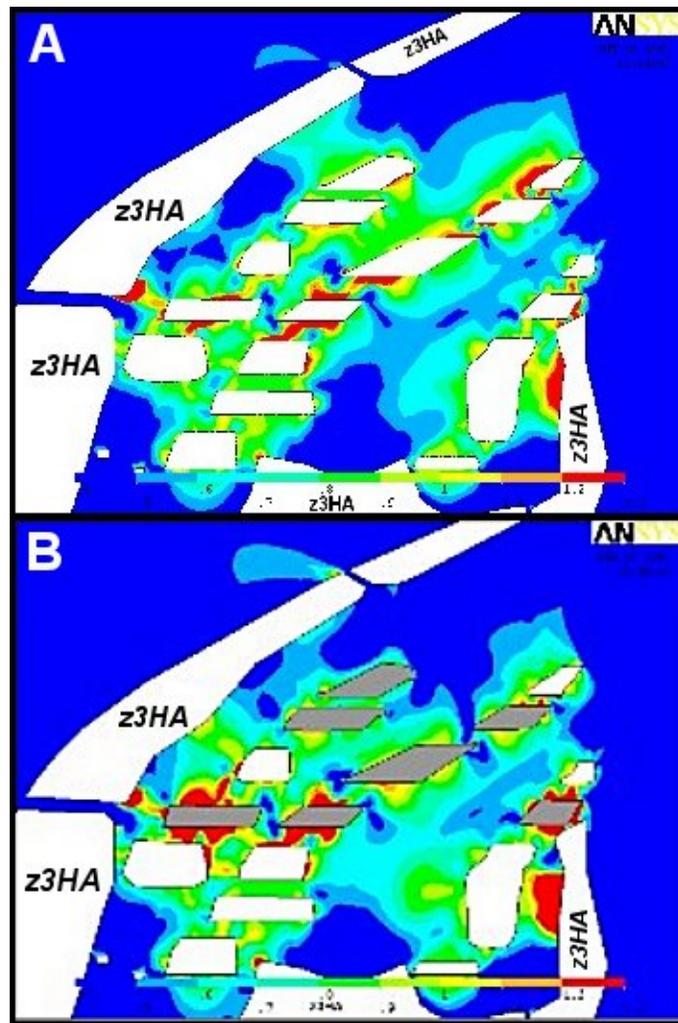


Fig. 4. Dilatancy criterion before (A) and after (B) backfilling (central part, Bartensleben); z3HA: “Hauptanhydrit” (‘main anhydrite’) of the Leine-Formation (z3). The yellow, orange and red areas mark a violation of the dilatancy criterion. The cavities are located in rock salts of the Staßfurt- (z2) and Leine-Formation (z3).

Geological induced potential pathways can not be improved. However, by numerical calculations it was shown that these structures are negligibly influenced by the liberated hydration heat keeping the temperature rise limits.

Extensive investigations showed that the amount of available water is limited, which might flow into the repository annually. As a result of stabilization and barrier improvement the maximum brine intrusion rate is estimated at a maximum value of 600 m³/a, i.e. under adverse conditions the remaining void volume of the repository mine will be filled up with brine in 3,000 years at the earliest. A basis of this statement is an effective shaft sealing.

As the emplacement structures are classified as not situated in the brine intrusion danger area the positions of sealing constructions are essential to fulfill *safety objective (3)*. The sealing constructions are situated in rock salt. As sufficient NaCl saturation capacity is available in the

mine as well as in the backfill material, because of the high content of crushed salt rock, no pathway is existing leading to unsaturated conditions in the near field of the sealing constructions. As a consequence of the expected brine intrusion rate ($< 600 \text{ m}^3/\text{a}$) during the post-closure phase sufficient time is available to reach a NaCl saturation of the salt solutions.

On the upper level the long-term safety analysis had shown that *safety objective (4)* is fulfilled by controlling the radiological exposition. As a basis for the calculations at the upper level it is assumed that the averaged cross section permeability k is lower than 10^{-16} m^2 . This secondary safety evidence criterion has also to be proved. The averaged cross section covers the EDZ, the sealing itself and the contact zone between EDZ and sealing. For the EDZ the limited permeability is shown by in-situ permeability tests.

For the sealing itself it is shown that construction material (salt concrete M2) is of adequate low permeability. Results of the laboratory tests are given in Table IV. In the case of the brine permeability the measurement limit of the apparatus is given, because the material behave hydraulically impermeable (12). However, it is not sufficient to restrict the investigations to the material properties. Furthermore it has to be shown that the sealing is constructed without fractures and fissures and that the construction is able to resist all stresses, strains and corrosion processes that may appear. This proof will be achieved by calculations controlling the temperature rise and the dilatancy condition in the sealing considering all relevant load cases. Actually, laboratory tests are performed to determine the dilatancy limit of the salt concrete.

Table IV. Gas (N_2) and solution permeability of the salt concrete M2; NaCl: sodium chloride (halite) saturated solution, Q: invariant solution of the quinary seawater system (Na-K-Mg-Cl- SO_4 - H_2O) saturated with respect to halite, sylvite, carnallite, and kainite (density about 1293 kg/m^3 ; 25 degrees Celsius).

storage conditions	pressure on the sample surface [MPa]	pressure of the gas or the solution [MPa]	Permeability [m^2]
gas permeability in dependence of the pressure on the sample surface			
dried samples	1.0 – 10.0	0,56 – 9,0	$5.4 \cdot 10^{-18} - 1.0 \cdot 10^{-18}$
gas permeability (storage of the samples at 20 °C and 60 % relative. humidity)			
20 °C / 65 %	2.5	1.8	$6.1 \cdot 10^{-20} - 1.5 \cdot 10^{-20}$
solution permeability			
pore spaces saturated	2.5	1.8	$\leq 3.0 \cdot 10^{-23}$ (NaCl)
pore spaces saturated	2.5	1.8	$\leq 6.0 \cdot 10^{-24}$ (Q)

Long-term stability of the seals is shown by numerical calculation coupling transport and corrosion processes. It is shown by sensitivity analysis that the material properties of the seals change very slowly. The sensitivity analysis and the laboratory tests to support the calculation data base and to verify the calculation results are still continuing.

To estimate the permeability of the contact zone, an in-situ investigation of comparable sealings is planned. By injection measures it is intended to fulfill the fluid criterion to assure that the permeability of the contact zone does not increase by internal fracturing, when loaded by brine

pressure. As different laboratory tests are not finished yet, the final sealing layout is not fixed. Nevertheless a conceptual study is already available, to assess to technical feasibility.

Concerning *safety objective (5)* the classical mining occupational health is guaranteed by classical mining safety measures in conjunction with a geo-technical surveillance program and a provisional concept, which describes technical and administration measures, how to deal with mining excavations, whose safety is not sufficient. The provisional concept is designed to avoid staying personal in such mining excavations. The handling with the backfill material will be regulated to guarantee occupational health. A transport of contaminated fluid is avoided, because of the ability of the salt concrete to fix the total transportation brine chemically and physically. This proof is performed by laboratory tests in conjunction with theoretical equilibrium examinations.

To assure that *safety objective (6)* is fulfilled recalculations are performed of aggressive substance transport into aquifers quantifying permissible substance concentrations in eluats. In these calculations the existing ERAM material inventory and the backfill material are regarded. The eluat values of the backfill material are controlled by laboratory tests.

CONCLUSION

During an operational phase of about 20 years the former salt and potash mine at Morsleben (Germany) serves as a LLW/ILW repository. The repository is now under licensing for closure. Hence a closure concept was developed taken into account the boundary conditions of the mine, e.g. the amount of the disposed inventory, the geologic/geo-mechanical situation, and the void volume of the repository. The concept is relying on an almost complete backfilling of the mining excavations with solid material (salt concretes) that is stowed by a hydraulic transportation system into the underground excavations (extensive backfill concept).

It can be summarized that the closure concept of the repository is able to serve all conventional and radiological safety objectives. The backfilling measures however are strongly coupled, a single measure can not be assigned to a single safety objective. Often a double function is present, e.g. the stabilization and the provision of a saturation capacity or the stabilization and the improvement of the geological barrier integrity.

A large number of safety related documents for the closure of the Morsleben repository are already available. It is intended to complete all safety-related documents within the year 2002.

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