Large scale in-situ experiments on sealing constructions in underground disposal facilities for radioactive wastes – examples of recent BfS- and GRS-activities

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Abstract:
This paper shows examples of in-situ constructions and laboratory tests that have been designed and implemented by BfS und GRS in order to demonstrate the technical feasibility of special constructions for the sealing of drifts and shafts in different salt formations.

Since a direct verification of the long-term functionality (for times scales envisaged in long-term safety assessments) of such constructions is often not possible, an overall understanding of the main chemical and physical processes involved needs to be developed. Such an understanding is required in order to extrapolate the evolution of a sealing system with a sufficient degree of reliability. Laboratory tests and large-scale in-situ tests are necessary and integral parts of the procedures for enhancing the process understanding.

Based on a safety case, BfS has developed a robust decommissioning concept for the closure of the low- and intermediate-level waste disposal facility Morsleben (ERAM) which also takes into account the retention of radionuclides by combined effects of different sealing components.

GRS has contributed to this concept with laboratory tests and modelling of the long-term behaviour of the sealing material “Salt concrete” foreseen for the sealing constructions in Morsleben. Salt concrete is based on the cement Portlandite i.e., on CaO. Furthermore GRS has also investigated the MgO based “Sorel concrete” employed by BfS for the Asse project. The chemical corrosion path and the subsequent permeability changes for both concretes have been investigated with test procedures developed in the GRS laboratory. GRS has also developed and tested in laboratory and in-situ experiments a new Self-Sealing material “Selbst Verheilender Versatz - SVV” (SVV, German for Self Sealing Backfill) which is able to achieve an instantaneous and long-lasting permeability reduction within the complex system consisting of the sealing construction and the Excavation Disturbed Zone (EDZ) upon brine intrusion.

The presentation demonstrates details of the concepts and highlights results from the in-situ experiments of BfS in Morsleben and the preceding GRS laboratory and in-situ tests.

1 BACKROUND

Radioactive waste disposal facilities in deep geological formations must safely be sealed for long time periods in order to isolate the wastes from the biosphere for at least several 100.000 years. Based on the site specific knowledge of the geological situation and possible evolution scenarios of the disposal system, safety concepts must be developed which verify that the goal of containment and isolation can be achieved. The extensive verification management in waste disposal uses natural analogues, modelling calculations, laboratory and large scale in-situ experiments as well as different prediction procedures, in order to also consider unavoidable uncertainties and inadequate knowledge. Before construction of a disposal facility, a long-term safety analyses must prove that no hazardous impact on the biosphere may occur by the waste disposed of. To enable this, the closure concept for underground disposal facilities has to include detailed planning for specific sealing constructions.

BfS and GRS are involved since more than 30 years in the German programme for underground disposal of nuclear wastes. BfS is responsible for the German disposal facility sites Endlager Morsleben (ERAM), Schacht Konrad and Schachtanlage Asse as well as the exploration site Erkundungsbergwerk Gorleben. GRS is a non-profit organization which deals with technical-scientific research and provides safety analyses and assessments for nuclear facilities including probabilistic risk analyses of nuclear power plants and waste disposal facilities in Germany and abroad.

2 IN SITU - EXPERIMENTS ON SEALING CONSTRUCTIONS FOR THE MORSLEBEN DISPOSAL FACILITY (ERAM)

2.1 Introduction and description of the Morsleben disposal facility (ERAM)

The radioactive waste disposal facility Morsleben (ERAM) serves as a disposal facility for low and intermediate-level radioactive waste. It is located in a former potassh mine in Saxony-Anhalt, Germany. Currently, the disposal facility is in the phase of decommissioning. The mine has four main floors and several interim levels. The shafts Bartensleben and Marie were excavated at the beginning of the last century. Due to the former mining for the production of potash and rock salt, the excavation ratio is very high in several parts of the mine.

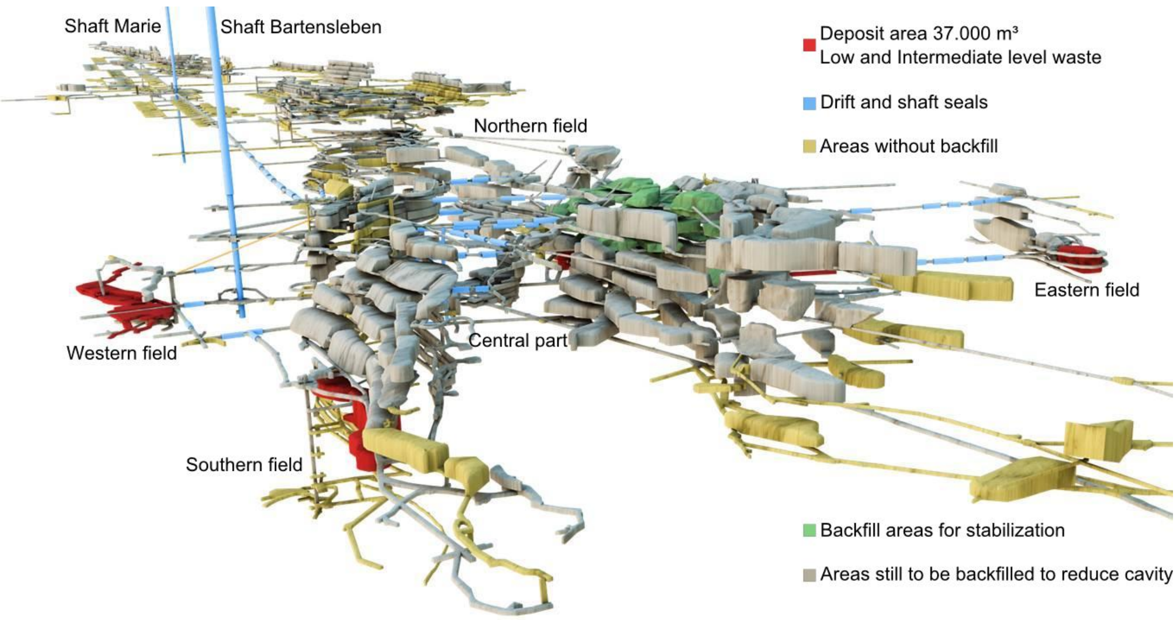


Fig. 1: ERAM - Mine fields of Bartensleben with disposal areas (in the foreground) and Marie (in background)

From 1971-1991 and 1994-1998 approx. 37,000 m³ radioactive waste were emplaced. The disposal areas are in the mine Bartensleben part of the mine at the 4th floor in the northern, eastern, southern and western fields and also, in lower amounts, in the central part (Fig. 1).

Fig. 2 shows a schematic geological east-west section through the Morsleben salt structure. The salt diapir was tectonically stressed and has a distinctive saddle and syncline structure. While the saddles are built mainly by salts of the Staßfurt series and consist of rock salt and potash, the synclines comprise rock salt and main anhydrite of the Leine series. The main anhydrite exists in blocks surrounded by salt because of the brittle material behaviour and the tectonic stress. The mighty caprock is possibly penetrated by the anhydrite blocks. The possibility of brine inflows into the mine openings along the main anhydrite is not very likely but it can not ruled out with certainty.

For further, mining excavations have to be backfilled. In addition, the disposal areas in each field have to be protected against possible solution inflow with sealing dams. Similarly, the shafts have to be closed and sealed.

With two exceptions all the sealing structures are located in horizontal galleries in rock salt. The exceptions, a sealing in the eastern field is located in the main anhydrite and one sealing in rock salt from the 1st to the 4th floor is vertical orientated.

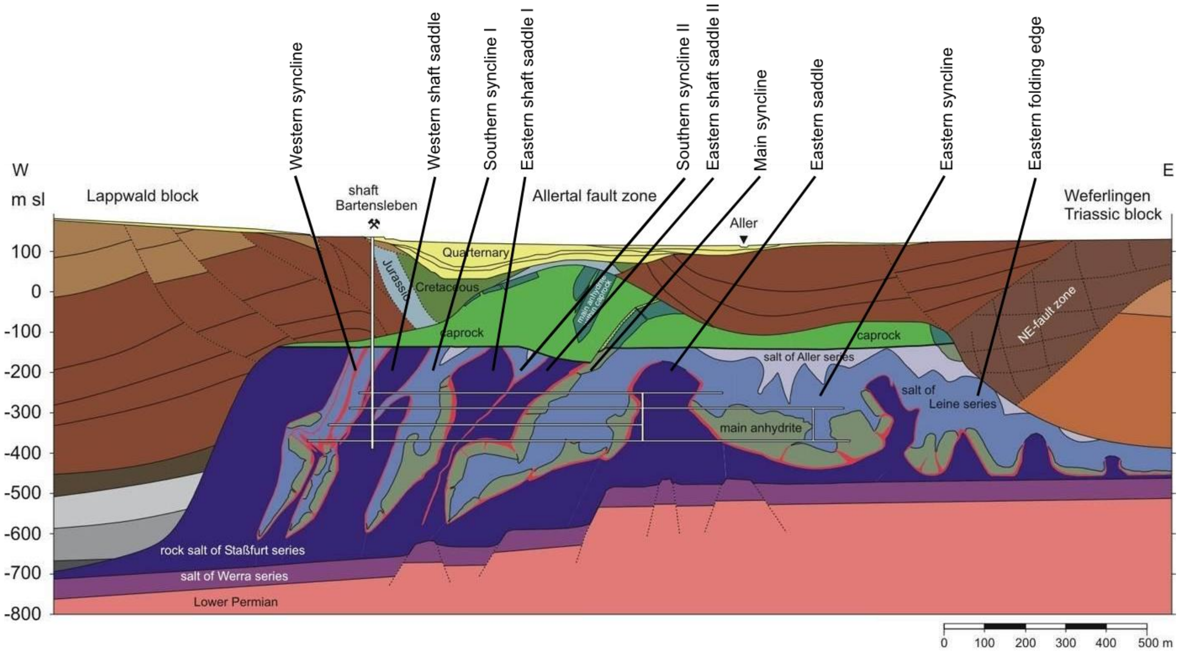


Fig. 2: Geological structure of ERAM disposal facility (west-east cross-section) with overburden

2.2 In situ-experiments related to sealing measures in horizontal drifts in rock salt

2.2.1 Functions of sealing dams in a disposal facility

If brine enters the salt structure, the sealings have the function to delay their inflow into the disposal chambers. The following considerations relate to sealing structures in rock salt because a first in-situ experiment was carried out in this formation. To delay the solution inflow, the migration pathway has to be sealed. The integral permeability of the system consisting of the sealing structure, the contact zone and the excavation damaged zone (EDZ) has to be below a certain limit. The necessary permeability can possibly achieved with a dam composed of salt concrete. In this case, the autogenous shrinkage of the construction material has to be considered [0]. To achieve an instantaneous sealing functionability the resulting joint between dam and contact zone must be injected with superfine cement for a strong and low permeable connection. The construction sequence shown below was designed in the conceptual planing phase to ensure compliance with the requirements of the sealing structures, which was formerly assumed in the safety assessment:

- Recut of the drift to remove the EDZ (criterion: permeability $k \leq 10^{-18}$ m²)
- Installation of the injection pipes for grouting the contact zone
- Concreting of the sealing structure composed of salt concrete
- Waiting to allow for the alleviation of autogenous shrinkage of the salt concrete (criterion: $\dot{\varepsilon}$ shrinkage ≤ $\dot{\varepsilon}$ creep rock salt)
- Injection of the contact zone

Once the construction of the sealing structure has been completed, a stress state will develop, which is characterised by normal stresses and shear stresses in the contact zone. The normal stresses result from the creeping of the rock. The shear stresses are based on a potential single-sided fluid pressure after an albeit improbable event of flooding the mine (Fig. 3).

Then these sealing dams will constrain possible infiltration of brine and the migration of radionuclides into the biosphere.

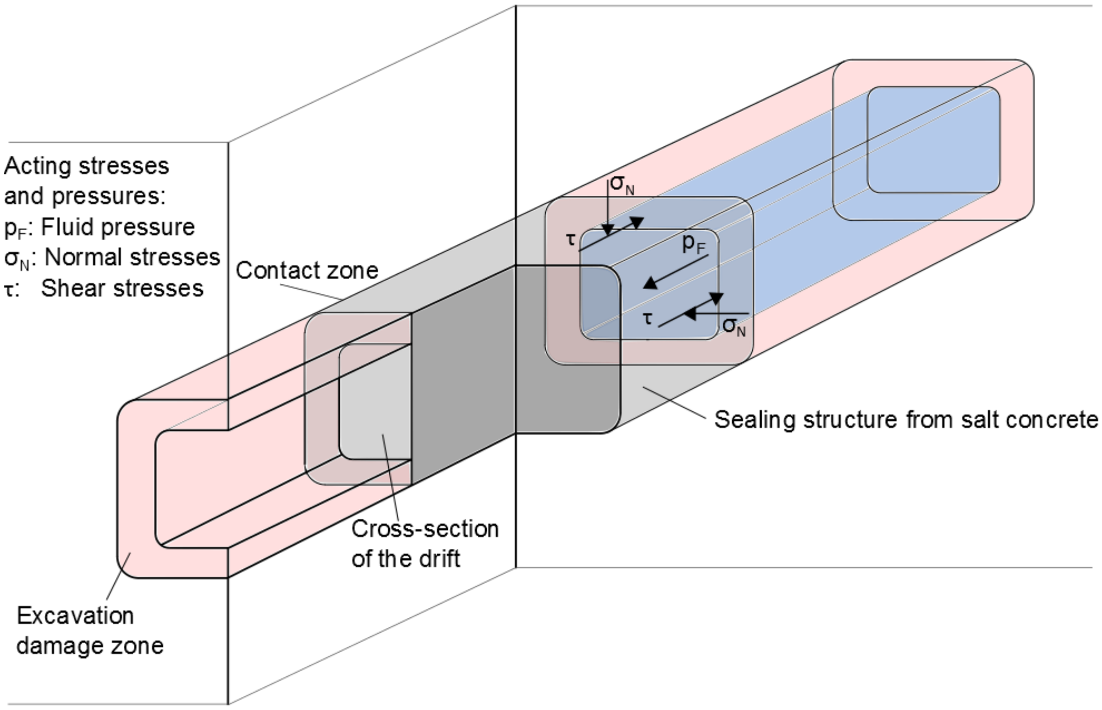


Fig. 3: Schematic of a drift seal [1]

2.2.2 In-situ test of a sealing structure in rock salt

As these sealing structures are no standard civil engineering structures, the functional capability of the sealings in rock salt is to be demonstrated by in-situ tests. Also in lack of generally accepted codes of practice there are many complex engineering performances necessary dealing with the dam materials, the behaviour of the host rock, the interaction between the dam and the excavation damaged zone.

To show that these sealing dams can be constructed with the quality assumed in the safety assessments an in-situ dam has been built as an experimental set-up comparable to the planned future sealing dams.

The design of the in-situ test has been chosen to represent a sealing concept where the drift seals located in rock salt are made up of one or more segments of salt concrete in lengths between 25 and 30 m. A succession of several segments will be separated from each other by plastic joints to prevent the occurrence of restraint stresses. Grouting of the contact joint between the sealing body and the surrounding rock salt will be carried out on at least one segment. In this respect the test construction consists of three system components, namely the sealing body made of salt concrete, the contact zone between the seal body and the surrounding rock salt and the rock salt excavation damaged zone (EDZ). All these components are observed during the in situ investigation.

Starting from the concept and the requirements for the future sealing dams - assumed in the safety assessments - a test site has been developed at the ERAM. Besides showing the technical feasibility of building a dam consisting of salt concrete and performing the grout injection of the contact zone the assumptions concerning material properties and material behaviour should be checked. Especially, the overall permeability of the dam is of interest. A measurement program was developed to cover these needs.

In 2010, a test drift and an accompanying drift were cut. The test drift (a blind drift) allowed to build a dam segment in a full scale (dimension of the construction: height: 4 to 5m, width: 4,5m, length: 25m). Hydrofrac measurements, convergence measurements and permeability measurements were carried out to examine and describe the initial state of the test site. In Fig. 4, the experimental set-up is shown.

At the blind end of the test drift, a pressure chamber - made of porous sandstone - allows to test the dam's permeability by building up a defined pressure (of gas or liquid). In the dam, the resulting pore pressure is measured in some cross-sections. In addition, instruments for monitoring stresses, displacements and temperatures are installed (Fig. 5). Fig. 6 gives an idea of the measuring device installation.

The concreting was performed in December 2010 and took about 20 hours for around 500 m³ salt concrete. After waiting for about 2 month to allow autogeneous shrinkage and thermal contraction to decay the grout injection of the contact zone was carried out. Fig. 6 gives an idea of the huge dimension of the completed construction.

The hydraulic tests in 2012 started with pre-tests using gas. The main test performed with NaCl-fluid started in June 2012 with a loading up to 0.3 MPa and is, after an increase of the pressure up to 0.7 MPa in May 2013, continued up to now. Additionally, boreholes are drilled in the dam to perform in situ measurements and to gain specimen for laboratory tests. The in-situ test consists of hydrofrac and permeability measurements, laboratory tests were carried out to determine strength and permeability.

A detailed description of the design of the in-situ test is given in [2]. In [3] the measurement program and investigation before construction is described in detail. First preliminary results of the measurements were presented in [4], [5] and [6].

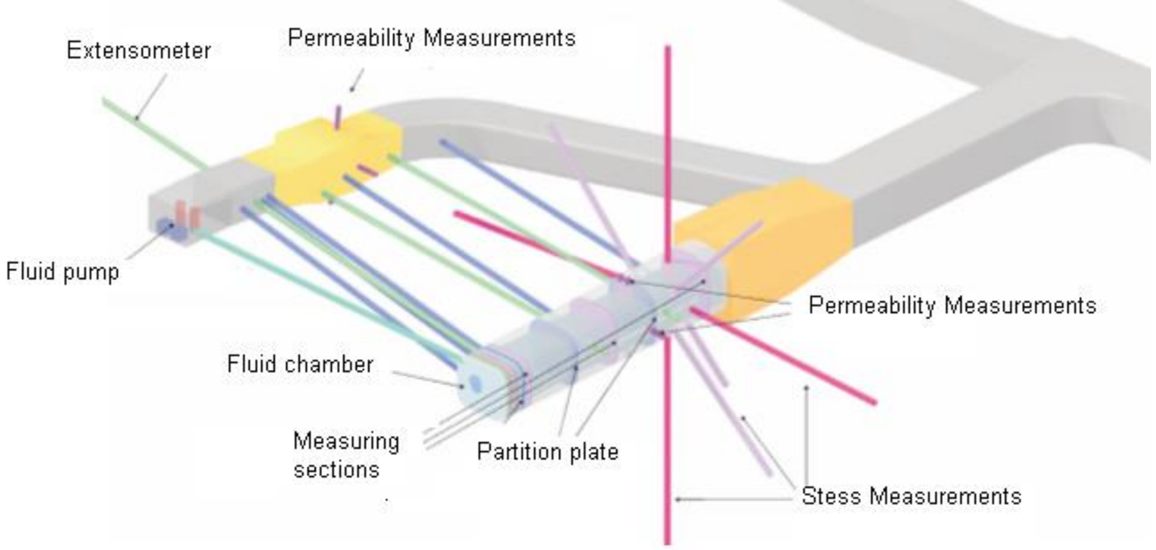


Fig. 4: In-situ test (view from above with accompanying drift)

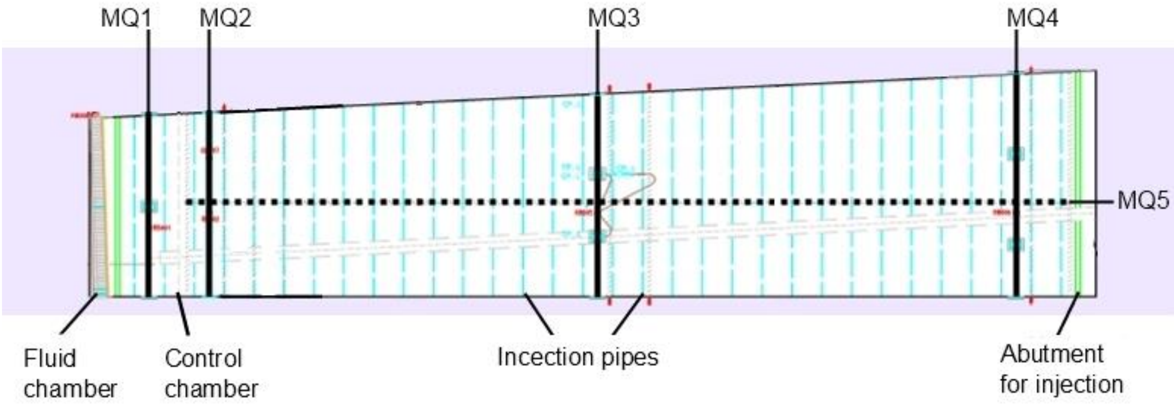


Fig. 5: Lateral cut section with measuring sections: MQ1 strain-, temperature-, pore-pressure-measuring; MQ2 strain-, deformation-, temperature-, pore-pressure-measuring; MQ3/4 strain-, deformation-, temperature-measuring; MQ5 deformation-, temperature-measuring; fluid-/control-chamber fluid-pressure-measuring

From spring 2013 up to now the main hydraulic test continues with an increased fluid pressure of 0.7 MPa in the fluid chamber. It can be seen that the injectable solution volume is continuously decreasing (flow rate recently below 0.2 ml/min).

Nevertheless there were some unexpected results obtained, which have to be interpreted in future work. E. g. micro and thin sections of core probes show some local cracks that are partially injected. How far these cracks - obviously mostly of limited extension - extend and if they are hydraulically relevant, is planed to be investigated. Regarding this local permeabilities, which may have a decisive influence on the corrosion behavior, further investigations will be carried out by in situ and laboratory measurements to obtain a better description of the permeability distribution. By using the actual available simple corrosion models the assumed long-term performance of the sealing structure could not be proofed entirely sucsessfull.

The successful construction of the in-situ test structure proofs its principal technical feasibility. Some technical improvements were identified. They are necessary especially during the injection process.

Numerical calculations to estimate the permeability applying the in situ measured fluid pressure as function of time result in an estimation of the integral permeability of the sealing structure in the range between 3E-18 m² and 8E-18 m² (state: April 2013). Due to the further decrease of flow rate and the continual increase of the normal stresses in the contact zone it can be assumed that an integral permeability k ≤ 10E-18 m² is accessible by the intended building design. To confirm this, the test will be continued.

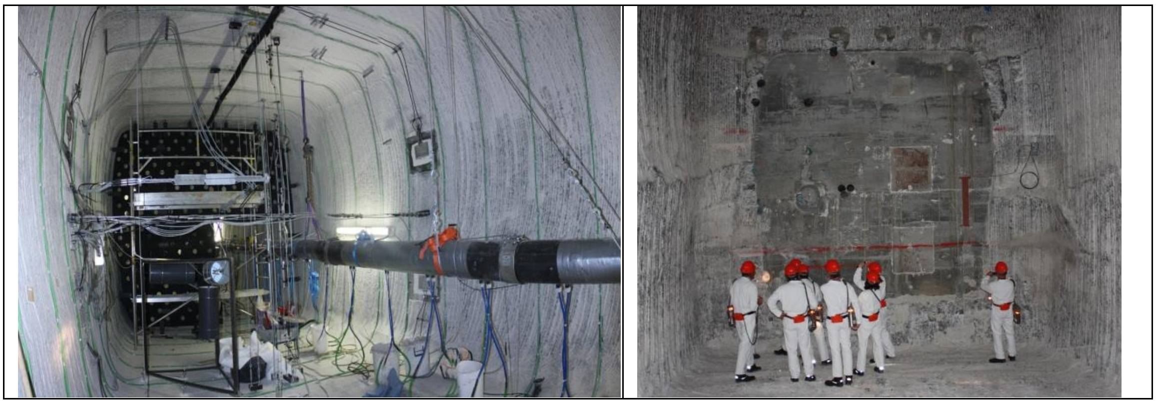


Fig. 6: (left) Photo of the test site with installed sensors, closed circular grouting pips, cladding tube and partitioning plate and (right) Photo of the air side of the completed test structure (with boreholes to perform in situ measurements and to collect specimen for laboratory tests)

2.3 In situ-experiments related to sealing measures in horizontal drifts in anhydrite rock

During the uplift of the salt dome the existing main anhydrite was exposed to considerable tectonic loads. As opposed to the rock salt the main anhydrite does not exhibit relevant creep behaviour but reacts brittly. Hence, it exists in single blocks. One sealing site to the eastern field is located in a relatively large anhydrite block, so that an over-hundred-metre-long sealing structure can be constructed here.

On account of the anisotropic stresses the brittle stress/strain behaviour leads to rock scaling or brittle failure processes in the area near the cavities, which can also be defined as EDZ. Besides it cannot be ruled out that joint systems exist. Despite normal backfill measures it cannot be assumed that isotropic stress states will develop in the long term due to the very low convergences of the rock. A decrease in the permeability of the EDZ is thus not to be expected; special technical measures need to be taken here. This also applies to the axial resistances in the contact zone structure/rock which need to be able to take up a one-sided fluid pressure.

In addition to the geomechanical aspects, damages near the contour strongly depend on the excavation or subsequent re-cutting procedures applied (drilling and blasting, cutting machines, band saws). Therefore the EDZ in the area of approx. 1 to 2 cm and the geo-mechanically influenced jointed areas reaching up to a few meters into the rock need to be considered differentially in the case of anhydrite.

2.3.1 In-situ test of a sealing structure in anhydrite rock

The requirements to be made on a sealing structure in the anhydrite result from the boundary conditions prevailing. As already described, there is only very low convergence to be expected in the anhydrite. As a result, it cannot be achieved that sealing material and host rock are positively tied through the rock's creeping, not even in the long term. Nor can a self-healing of the excavation-damaged zone be expected, as no isotropic stress state can arise in the rock.

Therefore a swellable material was being examined for the sealing structure in the main anhydrite, which indicates a pressure realizing the necessary normal stress in the contact zone between sealing material and rock right from the beginning and over the whole time of proof has to be established for. Through this effect cracks in the concrete are overpressured and, on the other hand, an inflow of saline solution into the contour should be prevented. A special magnesia or rather sorel concrete was used here as construction material whose required characteristics have already been proved in medium-scale laboratory technological examinations.

Likewise, there was no technical experience available to proof the swelling behaviour in the full scale. Hence, an in-situ experiment was required to show that the sealing dam can be constructed with the quality assumed in the safety assessments. Due to the fact that in short-term no suitable drift for larger constructions was available at Morsleben, the Bleicherode mine proved to be a suitable test site because of the similar anhydrite conditions.

For this purpose a test drift was driven by a smoothly blasting technology in 2010. Hydrofrac measurements, convergence measurements and geological mapping were carried out to examine and describe the initial state of the test site. The test design provides two brick-built abutments and a pressure chamber largely filled with gravel for permeability testing. The sorel concrete sealing body is located between the abutments. In order to conduct the temperature and swelling behaviour measuring devices have been installed.

In the early phase after concreting the construction material reached in the core region, a maximum temperature of about 110 ° C. The temperature near the side walls increased to values between 65 ° C to 85 ° C. The pressure profile at the start of the experiment showed the expected temperature-induced swelling pressure of up to 4.5 MPa. This decreased according to the decreasing temperatures in the structure which lasted about six weeks. After a few days the measured pressures reached values close to 0 MPa. In the following 10 to 15 days the so called second swelling phase occurs, at a concrete temperature of 40 ° C to 45 ° C. After exceeding the maximum swelling pressure of about 1 MPa the pressures decreased in all sensors continuously. After a few weeks he approached at a value of 0 MPa. The measured values show that the swelling pressure built up temporarily indeed - but not remained and fell at most measurement points up to almost 0 MPa. Furthermore, the used material heated up to more than 100 ° C in the core area which was much more than expected.

To clarify the causes of the non-lasting pressure a number of different studies have been conducted with respect to both the analysis of the procedure for the construction of the building as well as the evaluation of structural and material characteristics. For comparison, samples were tested which were removed from the (successfully) medium-scale laboratory examinations.

According to recent findings within the process of material testing (i. a. heated swelling-pressure tests) a swelling pressure of MgO-based (sorel) cements is excluded if the temperature exceeds the value of about 65 ° C in the structure (current state of research).

From today's perspective, a temperature limitation is not technical feasible of about 65 ° C in such a huge sealing structure without losing other important material properties. This example shows the importance of investigation of upscaling effects.

Because of the basic unsuitability of the used sealing material at the Bleicherode mine alternative sealing concepts including other materials and construction principles have to be investigated. The planning on this is ongoing and has not yet been completed.

Further in-situ testing activities for sealing structures in the anhydrite needs also to be planned and carried out. In this test the characteristic occurring in the anhydrite will have to be investigated in order to achieve that the integral permeability of the sealing structure, the joint and the rock will be maintained possibly through injection methods. As in rock salt, the gallery contour is subsequently re-cut before the sealing structure is constructed. This will be done to minimize the size of the EDZ.

2.4 In situ-experiments related to vertical sealing systems for vertical drifts and shafts

Vertical drift or shaft sealing structures - the conceptual design is discribed in [7] - are usually easier to build than horizontal seals. Nevertheless, objective evidence of functional principles are required. Therefore, experiments were carried out to provide a newly developed combined abutment-sealing element which consists of gravel and asphalt/bitumen. The pore space of the gravel is filled with asphalt/bitumen so that the combined abutment-seal element, besides the transmission of loads, prevents the afflux of overburden waters into the mine or rising brines from the mine. The bitumen/asphalt functions as a redundant and divers seal to other (e. g. bentonite based) sealing elements in the shafts.

This kind of abutment-sealing element is also to be used in the vertical drift location underground. Laboratory studies and one above-ground large-scale test (diameter 8 m) was carried out to optimise the construction technology. Another in situ-test is currently planned to investigate the technical feasibility and productibiliy under underground conditions.

3 GRS CONTRIBUTIONS TO SEALING CONCEPTS IN ROCK SALT AND POTASH SALT FORMATIONS

The GRS department of Process Analyses has concentrated on issues related to the long term stability of materials for sealing constructions in different salt formations in the presence of brines with different chemical compositions. The long term behaviour of construction materials depends on their resistivity against the corrosion by brines. In salt and potash mines however brines with very different chemistry can ocurr depending on the mineralogical composition of the salt formation. Rock salt layers consist of halite (NaCl), anhydrite ($CaSO_4$) and polyhalite ($K_2Ca_2Mg[SO_4]_4•2H_2O$). Water in cantact with these minerals forms NaCl-rich brines. Potash formations often contain carnallite ($KClMgCl_2•6H_2O$), Kieserite ($MgSO_4*H_2O$) and sylvite (KCl). In such potash formations $MgCl_2$-rich brines can occure. These two brines have a different corrosion potential for concrets with different cements The concretes employed in salt mines contain crushed salt instead of sand. The cements used in these concretes are based either on CaO or on MgO. In the so called “Salt concrete” the cement is Protlandite ($Ca(OH)_2$), i.e. the cement is based on CaO. In the “Sorel concret” the cement is MgO. Salt concrete is stable in an environment of rock salt formations with NaCl-rich brines. It is not stable in a potash rock environment with $MgCl_2$-rich brines. Vice versa, Sorel concrete is stable in contact with $MgCl_2$-rich brines and is easily corroded by NaCl-rich brines. This implies that in in mines with different mineralogy and possibly different brines, different concretes must be used.

GRS has developed a new material which in its opinion can be used independantly of the mineralogy of the salt formations and the chemistry of the brines. This material is based on $MgSO_4$. It is a fine grained dry material which can easily be emplaced and which developes its sealing function if it comes in contact with brines, independantly of their chemical composition. Therfor this salt based material was called “Self sealing Backfill” or SVV. A large number of laboratory experiments and small scale in situ tests indicate that SVV may be an alternative to materials with less geochemical compatibility to their mineralogical environment. However sealing constructions at the scale 1:1 have not yet been built. Such real scale constructions are essential in order to find out possible problems with SVV.

GRS has investigated Salt concrete, Sorel concrete and SVV in the laboratory at different scales. Lage scale sealing constructions with Salt concrete and Sorel concrete were built and investigated by BfS in the disposal facilities Morsleben and Asse. These materials are forseen in the decomissioning concepts of these LLW disposal facilities. The more recent development of SVV has been investigated by GRS in in-situ tests large diameter horizontal and vertical boreholes in the mines Asse and Teutschenthal.

Examples of the BfS large scale in-situ constructions in Morsleben with Salt concrete have already been shown in the previous chapters. The following chapters give an insight into the methodology developed by GRS and the results obtained for the sealing materilas Salt concrete and SVV.

3.1 Investigation methodology

For the investigation of the long term behaviour of the different construction materials a twofold approach was adopted. Laboratory experiments at different scales as well as in-situ experiments were conducted and combined with mathematical modeling. Geochemical and reactive transport models were developed in order to reproduce the experimental results. Only if the experimental results can be reproduced satisfactorily by mathematical modeling the complex processes are well understood. This is a precondition for the extrapolation of the results beyond the short time frame of the experiments and for reliable prognoses of the long term behavior of the sealing constructions.

3.1.1 Laboratory investigations

The primary objective of the laboratory investigations was the improvement of the process understanding of the chemical corrosion processes which are intimately linked to changes of the porosity and the permeability of the different sealing materials. Futhermore the input parameters for the mathematical modeling had to be determined. These parameters are the chemical compositions of fluids and solids,the mineralogical composition of the uncorroded and the corroded materials a different stages of corrosion, porosity and permeability at the beginning and in diferen stps af the advancing corrosion etc.

Different geochemical and hydromechanical experimental procedures were developed by GRS in order to investigate the interactions of the different materials with the relevant brine compositions.

<u>3.1.1.1Geochemical experiments</u>

An experimental procedure, the so-called “cascade experiment” was developed for the investigation of the chemical reaction path of the interactions of construction materials with brines [8]. Fig. 7 shows the scheme of this procedure which is based on a succession of batch experiments (cascades). Basically it is a titration experiment. In the first batch a certain volume of fine grained solid is mixed with a certain volume of brine. The reaction takes place in an air tight vessel which is shaken continuously in an over head rotator. After several days all soluble components of the solid have been leached. The new brine composition is in chemical equilibrium with the corroded solid. The atainment of the equilibrium must be checked with chemical analyses of the brine. If the chemical composition does not change any more the equilibrium is reached. Than the brine is separated from the solid and transferred to another vessel where new solid is added. This procedure is repeated for several times. During the succession of these batch experiments in each step (cascade) more solid is added to the initial brine. Thus it is possible to find out how much solid can be corroded by a certain amount of brine until final equilibrium is reached. In each step the solid/liquid ratio is well defined and the attainment of the chemical equilibrium is achieved. In each step only a part of the initial brine volume can be recovered and used in the next cascade. Therfore the cascade experiment is finished when not enough brine can be recovered for the next cascade.

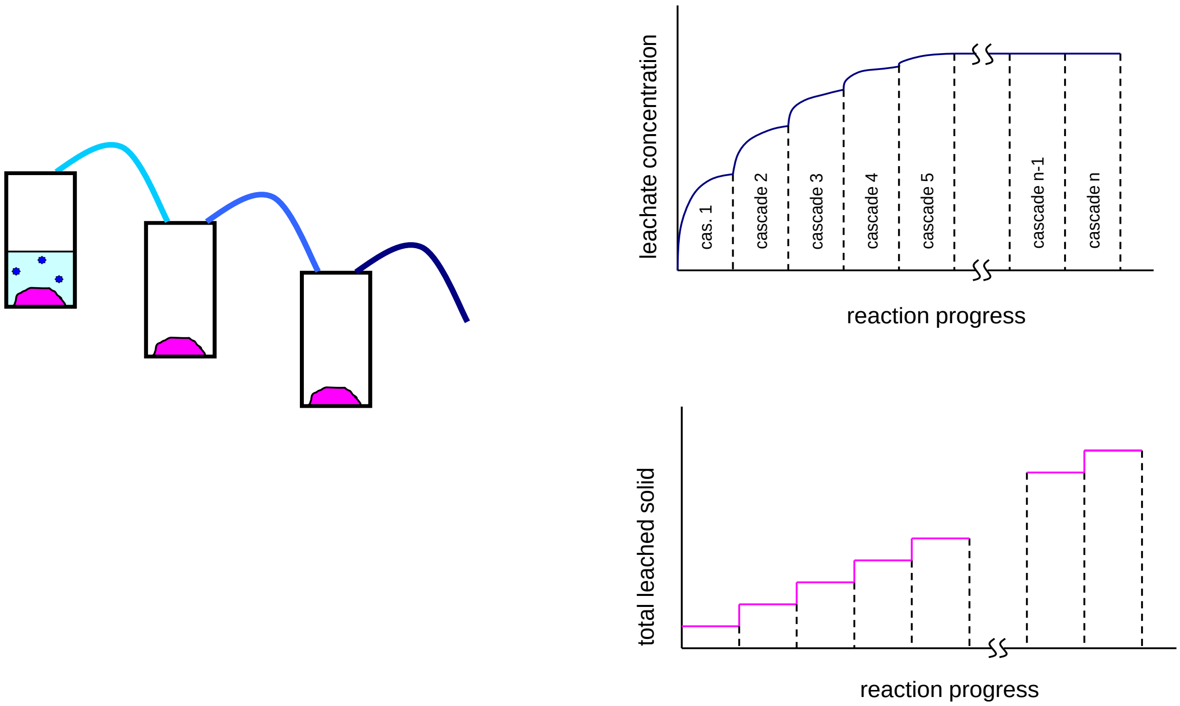


Fig. 7: Principle of cascade leaching experiments [8]

The cascade experiments simulate the intrusion of brine into the concrete seal and the chemical changes due to the corrosion. This titration experiment reproduces the corrosion reaction step by step with increasing solid/liquid rations until a final chemical equilibrium is reached, i.e. until the corrosion is complete at the solid/liquid ratio attained in the experiment.

3.1.1.2Hydro-mechanical laboratory experiments

In the long term safety analyses the changes of permeabiliy of the sealing structures over time are key elements. The permeability contoles the amount of brine which can come in contact with the waste and mobilise radionuclides. The permeability of the initial uncorroded material is well known. Materials are deigned in such a way that the initial permeability is low, in the order of 10-18 m². This important boundary condition should not change over time. Only materials which are in chemical equilibrium with their environment can fullfill this requirement. The geochemical investigations show to what degree this requirement can be fullfilled. If corrosion processes can not be avoided it must be known how intensive they are, how fast the corrosion deteriorates the materials and how much the initial peremability is changed over time.

An experimental set up was developed which allows to determine the time dependant move of the corrosion front in the materials as well as the associated chemical changes of the intruding brine.

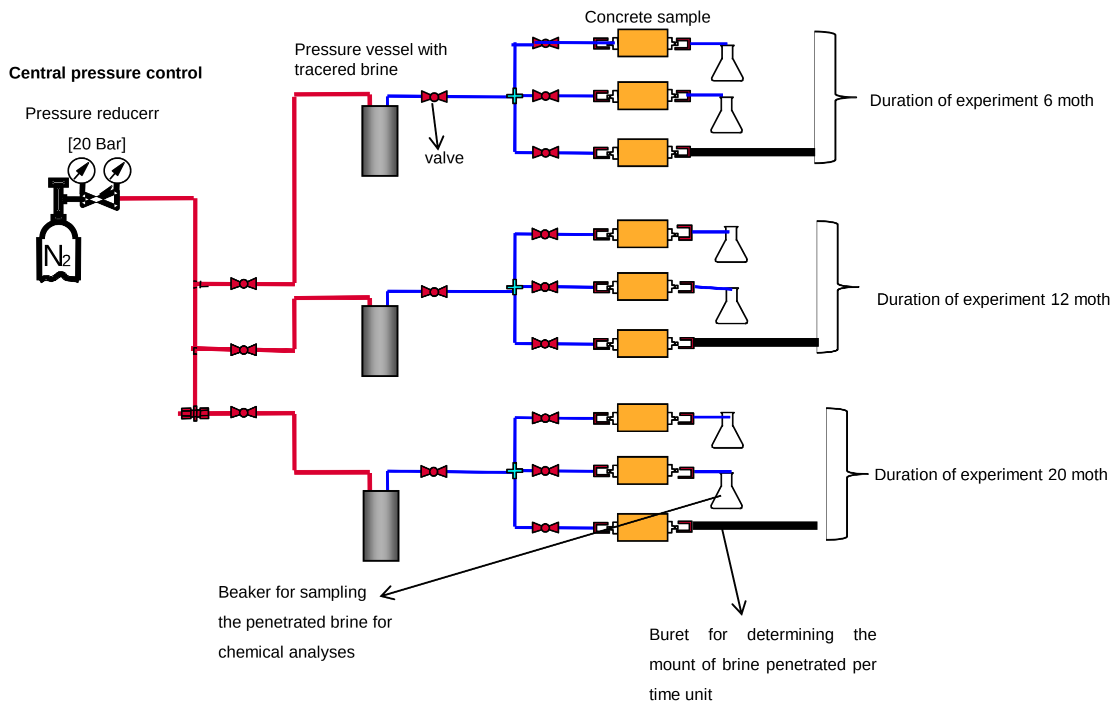


Fig. 8: Experimental set-up (percolation experiments) for measurements of permeability changes due to the interaction of brine with concrete [9]

Special procedures were necessary for the investigation of permeability changes and swelling pressure of the Self Sealing Backfill material SVV.

SVV is a fine grained free flowing dry salt or salt mixture. It consists basically of anhydrous $MgSO_4$. Other salt minerals like halite and sylvite can be added. The intrusion of brine into the large initial pore space of the dry material triggers a reaction that leads to the formation of a brine tight seal. The reaction leads to the hydration of the anhydrous $MaSO_4$ and to a large volume expansion. If the volume in which the expansion can take place is confined (in pressure cells in the laboratory or between bulkheads in large scale in-situ experiments) the initial pore space is filled and a swelling pressure develops. The intruded brine is consumed by the hydration process. The initial high porosity of the dry SVV material (60 vol.-%) is reduced to 2-5 vol.-% of isolated pores. The volume increase leads to a considerable crystallization pressure. The porosity/permeability relationship resembles that of highly compacted crushed rock salt backfill. The mechanical properties are comparable with the values of undisturbed rock salt.

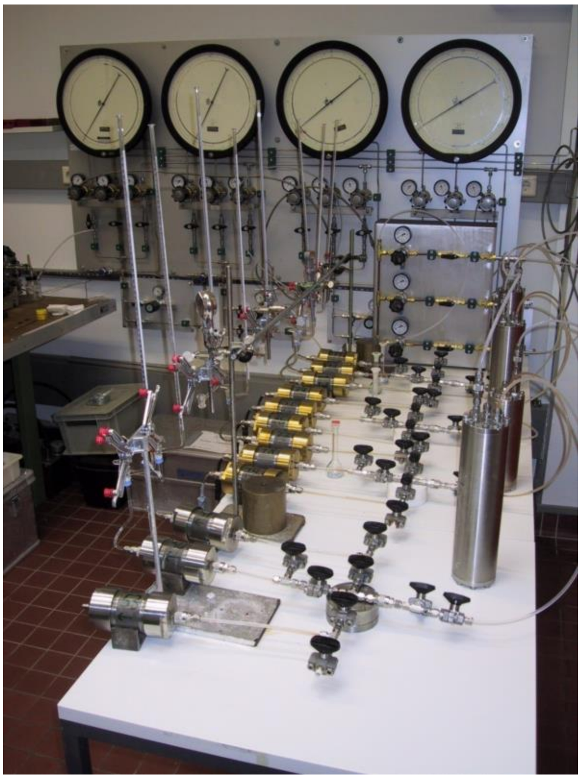


Fig. 9: Photograph of the experimental set-up for measurements of permeability changes during the interaction of brines with concretes [9]

Fig. 9. shows how fluid pressure, crystallization pressure and injected brine volumes are changed during the flooding of SVV with brines. Fig. 10 and Fig. 11 show the experimental set-up for the measurements of permeability and swelling pressure of SVV in contact with brines.

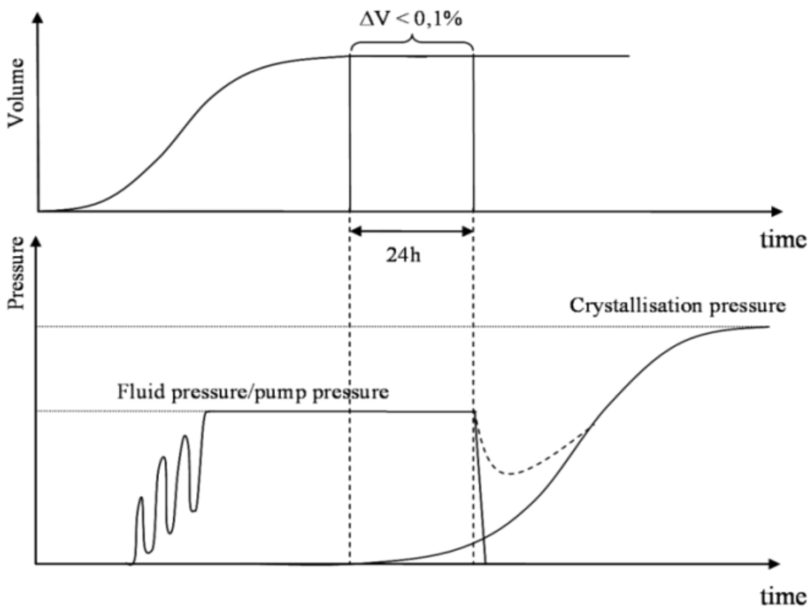


Fig.10: Schematic diagram of the development of fluid pressure, crystallization pressure and volume changes during the flooding of SVV with brines [10]

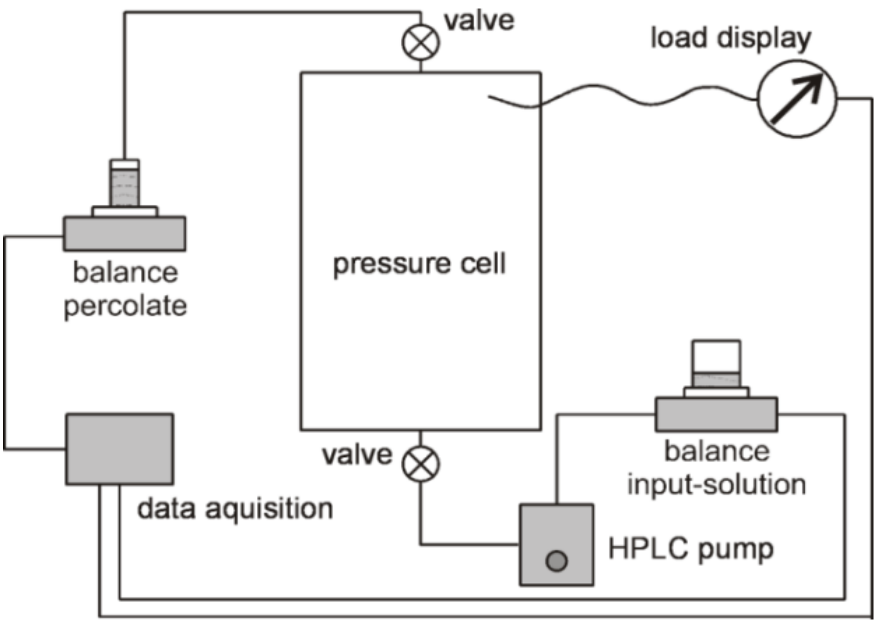


Fig. 11: Schematic diagram of the equipment for measurements of the development of permeability and crystallization pressure of SVV flooded with brine [10]

Fig. 12: Different scales of the experimental set-up for the measurement of swelling pressure of Self Sealing Backfill (SVV) in contact with brines - (left) pressure cells of different sizes and geometries, (right) large pressure tubes [10]

3.1.2 Large scale in-situ experiments with SVV

In laboratory experiments all the relevant data concearning the behavior of SVV in contact with different brines had be determined. However in-situ sealing constructions with SVV were still needed in order to demonstrate that this new sealing material is realy siuatble for the construction of large scale horizontal and vertical sealing elements in different salt environments. Figures 13, 14 and 15 show examples of such in-situ constructions in the LLW disposal facility Asse and in the former potash mine Teutschenthal.

Fig. 13: Preparation of a large borehole (1 m in diameter) in a rocksalt formation in the Asse mine for the emplacement of a SVV seal flooded with a NaCl-rich brine [11]

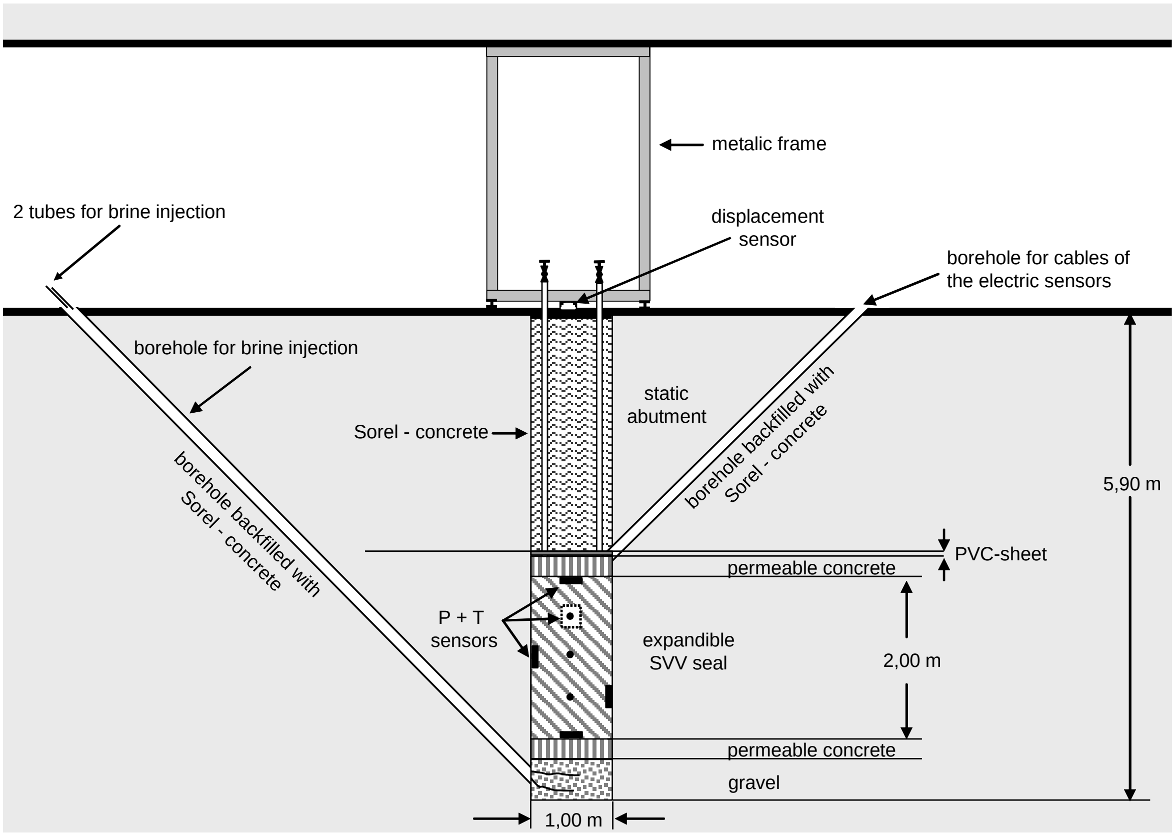


Fig. 14: Concept and instrumentation of a vertical borehole seal of SVV flooded with $MgCl_2$-rich brine in a Carnallitite potash formation in the Asse mine [12]

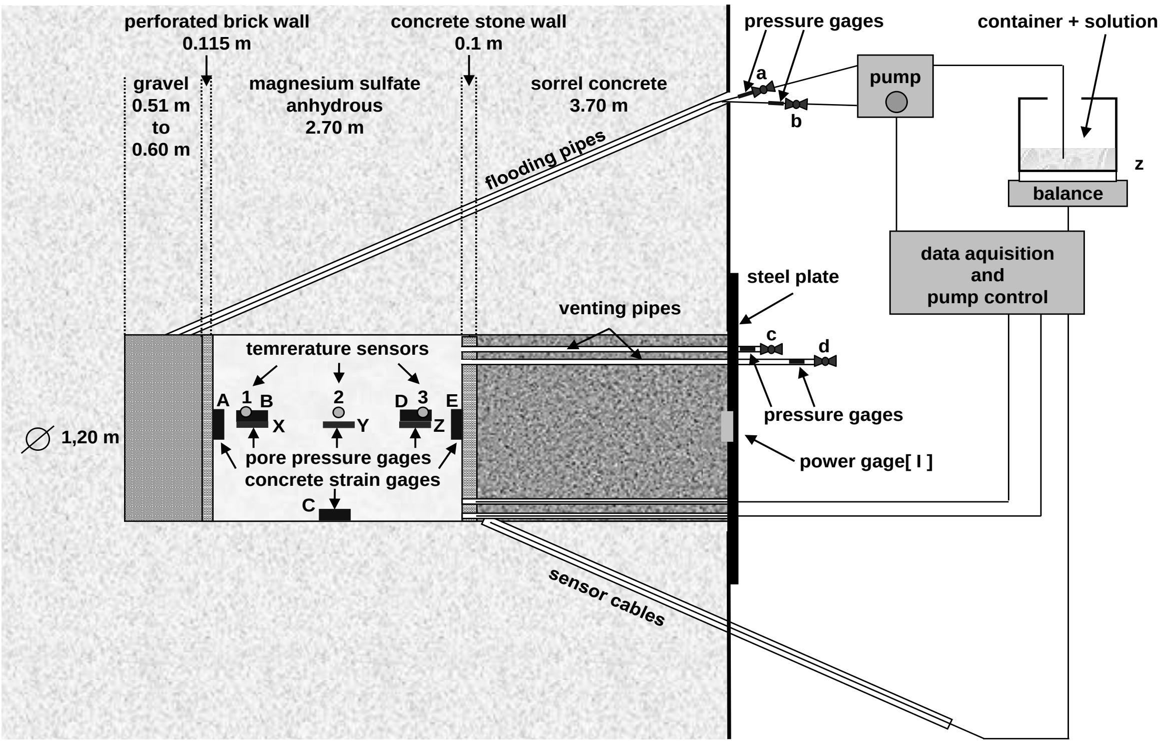


Fig. 15: Concept and instrumentation of a horizontal borehole seal of SVV flooded with a $MgCl_2$-rich brine in the Carnallite-Tachydrite potash formation in the former potash mine Teutschenthal [12]

3.1.3 Geochemical modeling

The combined results of experiments and geochemical modeling provide essential information needed for the long term safety analyses.The target of the geochemical modeling is to reproduce the experimetal results regarding the reaction path of the corrosion of the different materials with different brine types. If the corrosion process is well understood and can be extrapolated beyond the experimental limit the long term behaviour of potential materials can be demonstrated. Siutable long term stable materials can be distinguished from unstable materilas.

Once the corrosion process is well understood and all involved initial and newly formed mineral phases are well defined and if their partial molar volume is known the volume changes can be derived from the modeling results. These volume changes are responsible for the changes of permeabilities. All these information are essential for long term safety calculations.

For the geochemical modeling the following input parameters are needed:

- amount and composition of brine and solid,
- mineralogical composition of the solid new mineral phases which are built during the corrosion process
- complete and adequate thermodynamical database needed to describe mathematically the corrosion reaction

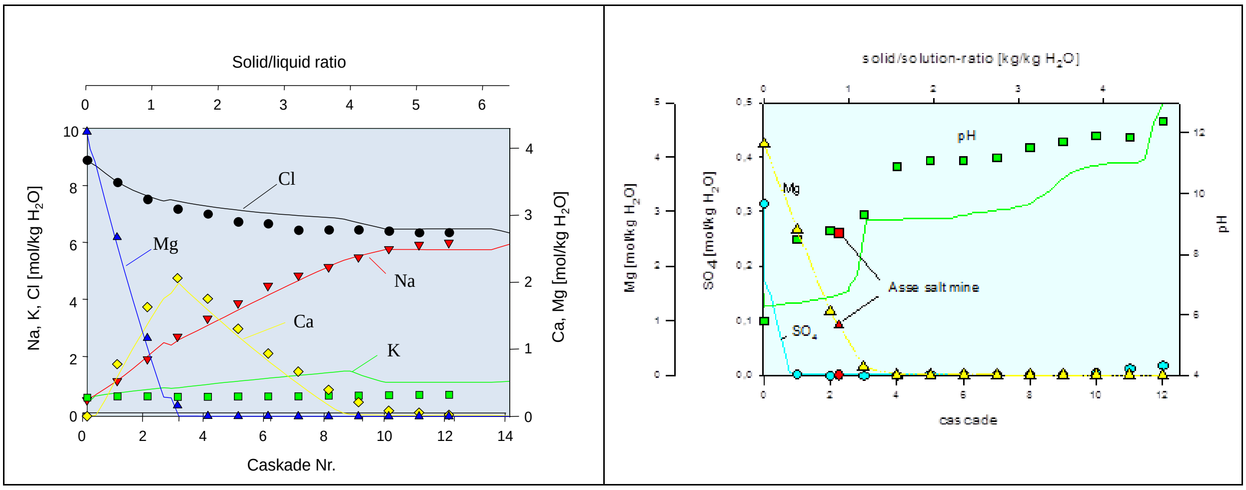


Fig.16: Comparison of experimental results (symbols) and the results of geochemical modeling (continuous lines) of the corrosion reaction path of salt concrete with a Mg-rich (IP21) brine [13],[14]

3.2 Results

The most important results of the extensive investigation programs on Salt concrete and Self Sealing backfill (SVV) are presented below.

3.2.1 Salt concrete

The good agreement of experimental results with the geochemical modeling (Fig. 16) shows that the corrosion of Salt concrete with a Mg-rich (IP21) brine is well understood. Similar good agreements were obtained for the interactions of Salt concrete with NaCl-rich brine. These results demonstrate that Salt concrete is stable in rock salt formations with Halite, Anhydrite and Polyhalite but that it is not stable in potash salt formations where Mg-rich brines may occure and may lead to a fast corrosion and increase of permeability.

The corrosion mechanisms of Salt concrete in contact with the corrosive Mg-rich brine are shown in Fig. 17. The left part of the figure shows the diffusion controlled corrosion process in the undisturbed concrete matrix. The right part of the figure shows the much faster corrosion (permeability changes) of the Salt concrete on cracks. At the time beeing only the matrix corrosion is well understood and can be modeled by a reactive transport model developed by GRS and the University Hamburg Harburg [14].

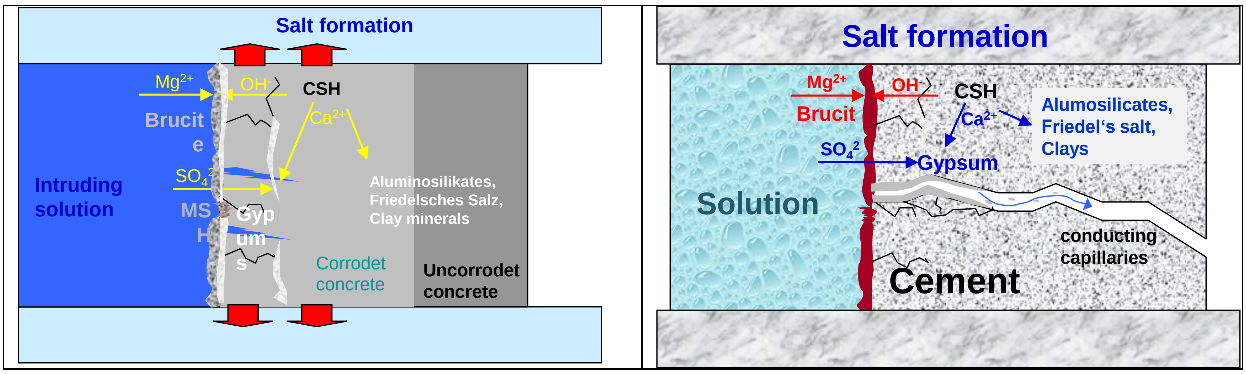


Fig. 17: Schematic representation of corrosion processes in salt concrte due to the interaction with brine (left) matrix corrosion, diffusive magnesiumsulfate attac and (right) advective magnesiumsulfate attac (in [15] after [16])

The main results concearning the behaviour of salt concrete in contact with a corrosive Mg-rich brine obtained so far can be summarized as follows [17], [18]:

The cascade experiments showed for increasing solid/liquid ratios up to 1.5 an increase of Ca2+ and a linear decrease of Mg2+in solution (Fig. 16 left). The extrapolation of these results indicate that 5.57 m3 of Salt concrete (M2-4) can be totally corroded by using up the Mg2+ content of 1 m^3 of Mg-rich IP21 brine. If the Salt concrete composition M2 is used the corrosion potential of 1 m^3 of IP21 brine is only 2.5 m^3. The corrosion potential of the IP21-brine for the M2 Salt concrete could also be deduced from percolation experiments (see Fig. 8). The figure obtained from this independantly calculated corrosion potential is lower (1.27 m^3/m^3) than the one obtained from the cascade experiments. This lower value can be due to kinetic effects.

The geochemical model calculatons indictate that magnesium-silicate-hydrate (MSH) phases Kerolite or Talc or Antigorite must be formed during the corrosion. Only if one of these phases is accepted in the modeling the good agrrement betwenn the experimental and calculated development of the brine chemistry can be obtained. So far neither one of these MSH phases could be detected by XRD analyses, but the probability that one of them occures in reality is very high. The range of corrosion potentials obtained from the experiments can be obtained from the model calculation. The higher or lower corrosion potential depends on the actual MSH phase present in the system.

Reactive transport calculations show that the corrosion front is very sharp and that it moves very slowly through the sealing structure. Therfore an slightly increase permeability in the corroded part of the structure presents no problems for the long term performance of the sealing structure.

These results however are only valid if no major cracks in the structure occure.

For the dam of Salt concrete constructed by BfS in in a rocksalt section of the Morsleben disposal facility (see chapter 2.2.2) it was assumend that no cracks will appear and that a very slowly moving sharp corrosion front driven only by diffusion (according to the scheme in the left part of fig. 17) will lead to a long lasting very low permeability of the sealing system.

In practice cracks were detected which have to be taken in account. It can not be excluded that a much faster corrosion on cracks driven by advective flow of Mg-rich brine may increase the total permeability of the salt concrete structure faster than expected.

Such a corrosion on cracks driven by the advective flow of brine can not yet be modeled. GRS has developed an experimental procedure which shall produce the experimental basis for the development of a mathematical reactive transport model.

3.2.2 Self sealing material (SVV)

According to the opinion of the GRS in technical barriers like drift seals or borehole seals SVV can be confined between static abutments and flooded with brine. Due to the volume increase a crystallization pressure builds up which renders the material impermeable to further brine inflow.

The results of the laboratory tests and medium-scale in-situ experiments with SVV can be summarized as follows [12]:

- initial porosity of dry SVV: 30 - 40 vol.-%
- residual porosity of SVV after reaction with brine: 2-5 vol.-%
- crystallisation pressures: 3 – 9 MPa; crystallization pressures depend on the mineralogical composition of the dry SVV, the chemical composition of the brine and the solid-solution ratio (which can be influenced by the brine pressure)

- mineralogical composition of resulting SVV seal depends on initial mineralogical composition of dry SVV and of chemical composition of brine
- permeability of reacted SVV is generally very low, between 10-18 – 10-21 m²
- porosity-permeability relationship of reacted SVV is comparable to that of crushed rock salt
- geotechnical properties of SVV seals after reaction with brine show a large scattering but in general they are comparable to the properties of rock salt

The crystallisation pressure in a SVV seal can be controlled by varying the above mentioned influencing factors. The crystallization pressure not only leads to a very low permeability within the SVV sealing element but also to the closure of the excavation damaged zone. SVV seals may lead to a very low permeability of the entire sealing system, including the EDZ.

The initially metastable mineralogical composition of the hydrated SVV seal will gradually be transformed into thermodynamically long-term stable mineral assemblages. The mechanical properties of SVV are comparable to those of rock salt.

Mineral assemblages obtained in the experiments and measured by X-ray diffraction agree well with modeling results. The geochemical modeling (Fig. 19) allows to quantify the short- and long-term volume changes in the system and demonstrates that in the long run stable mineral assemblages will be obtained.

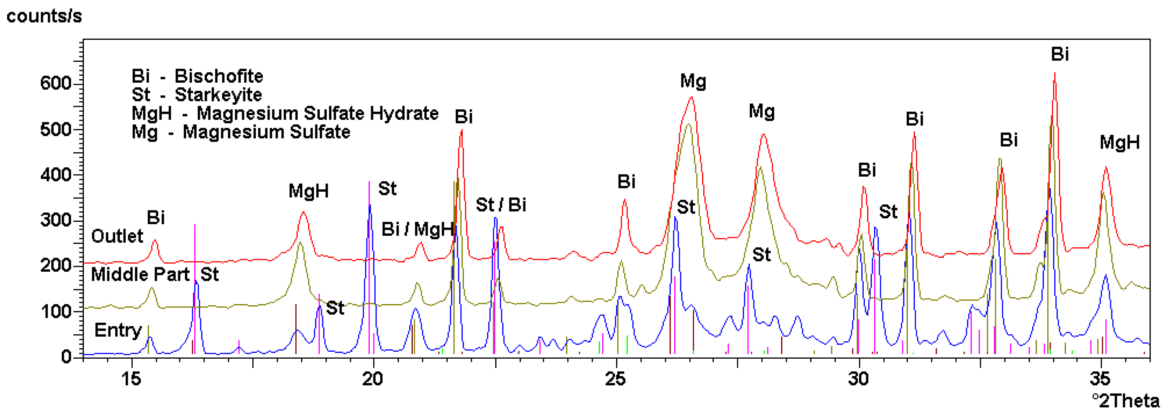
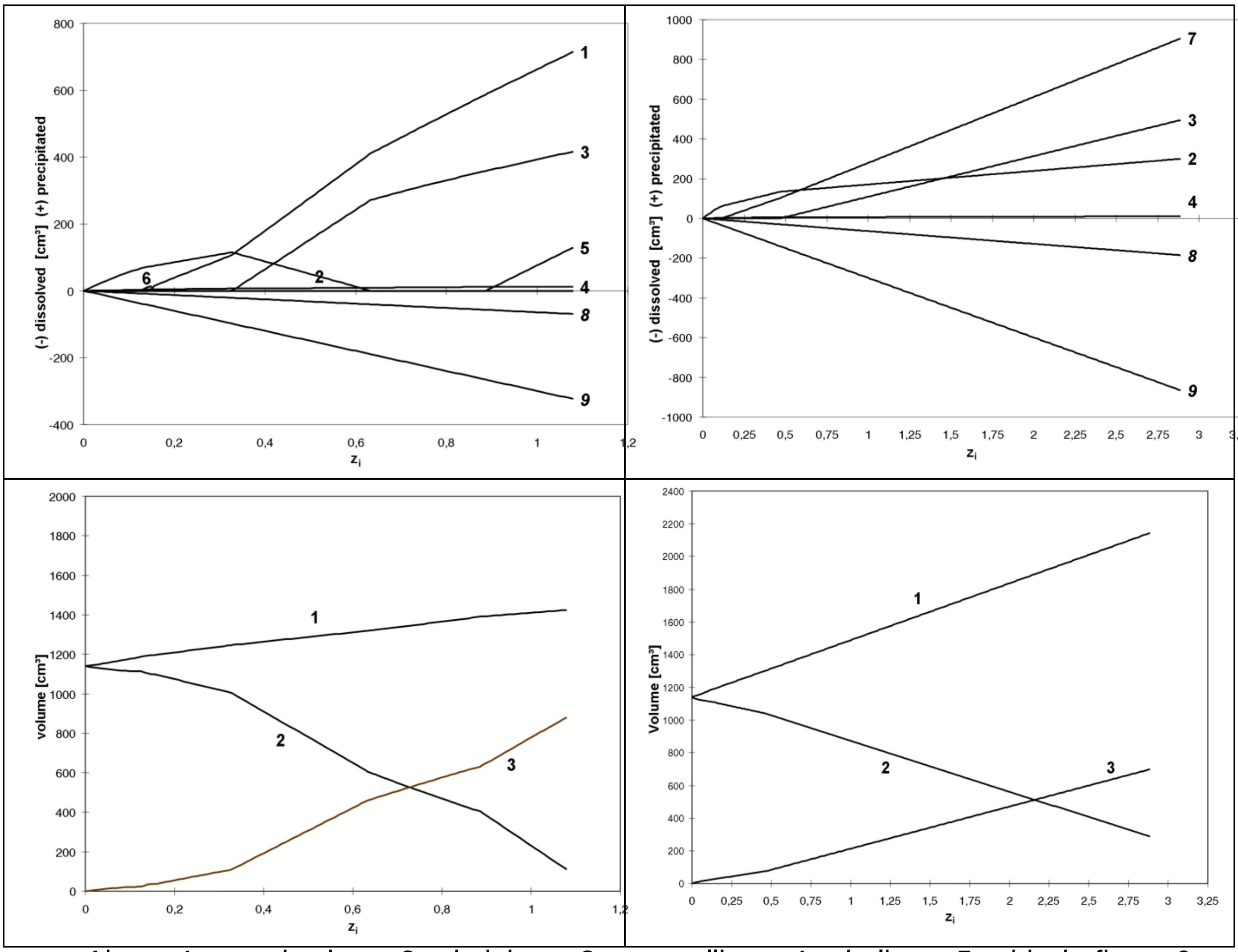


Fig. 18: XRD pattern of the mineral assemblages of SVV reacted with Mg-rich (IP21) brine at different distances from the point of brine inflow [11]



Above 1 = starkeyite 2 = kainite 3 = carnallite 4 = halite 5 = bischofite 6 = hexahydrite 7 = kieserite 8 = sylvite 9 = anhydrous magnesium sulphate

Below 1 = volume of the system (difference between the sum of solution and consumed anhydrous magnesium sulphate and the sum of precipitated minerals) 2 = volume of the solution 3 = volume of precipitated minerals

Fig. 19: Geochemical modeling of the interaction of self-sealing backfill (SVV. 80 wt-% MgSO4 anhydrous + 10 wt.-% halite + 10 wt.-% sylvite) with a Mg rich (IP21) brine saturated with halite-carnallite-kainite-polyhalite-sylvite [11]

The different in-situ experiments in salt and potash formations have demonstrated that SVV could be an option for an alternativ construction material of brine tight seals in any mineralogical environment in salt formations with any brine composition. SVV seals can resist to high brine pressures, even in mechanically disturbed rocks [19]. To proof the technical and functional feasibility further studies (real scale sealing constructions) are required.

4 SUMMARY AND CONCLUSIONS

In the scope of the safety case, evidence of the functionality of the sealing structures must be provided. In the decommissioning concept, the sealing structures take over the function of delaying the contact between solution and waste for as long as possible in case of a relevant brine inflow (improbable scenario). As it cannot be forecast reliably whether an inflow of solution into the mine cavities will occur and, if so, when it will occur and at what rate, and what the composition of the solution will be, solely the initial state of a sealing structure built according to plan can be measured and used for the furnishing of proof.

Suitable forecast models therfore must be available or be developed which can predict reliably the long term behavior of the sealing structures. The forecast must take into account the exact boundary conditions and must therfore be done location-specifically for the entire period under consideration.

However, the following has to be taken into account in the determination and interpretation of the processes and parameters used in these forecast models:

- The reliability of the forecasts is significantly influenced by the input parameters' quality.
- The in-situ sealing test structures' characteristics can be influenced by the measuring equipment or the measurements themselves.
- The target value for the parameters to be determined is frequently in the range of the limits of detection of the measuring systems used.
- Within a realistic period of measurement, no stationary behaviours are yet to be expected. Therefore the extrapolation quality is subject to uncertainties.
- Not all possible system states (e.g. increase in pressure with different, particularly slow rates, corrosion effects in the case of different compositions of solutions, influence of saturation,…) can be simulated in situ.

Taking into account all these aspects it becomes clear that the measurements gained in the scope of in-situ tests contribute essentially to the understanding of the system and thus also to the improvement of forecast models. A direct evaluation of the functionality or, respectively, confirmation of originally made model assumptions is only reliable after a comprehensive interpretation has been carried out. As a key component, the discussion of the interpretation results has to be taken into account in the documentation of the safety case.

Ultimately, deviations from the assumptions taken originally into account in the safety assessment may result from the outcomes of the exact planning of the decommissioning measures of disposal facilities and the in-situ tests performed. Then a decision needs to be made as to whether account must be taken of these deviations by modification of individual elements of the decommissioning concept or by adaptation of the safety assessment, or both.

On the bases of laboratory experiments GRS has developed a theoretical model which reliably describes the matrix corrosion of salt concret. Presently it seems that this model must be extendet towards the mathematical description of the corrosion on cracks driven by advective flow of the corroding brine. Such an advanced model needs a reliable experimental bases. GRS has developed the procedure for the required experiments.

Furthrmore GRS has developed a new sealing material, a Self Sealing Backfill, SVV. In laboratory and medium-scale in-situ experiments it was investigated that SVV could be a suitable material for the construction of sealing elements in salt formations. The properties of SVV are compatible with different salt formations like rock salt, carnallitite and tachhydrite. A high sealing capacity against salt solutions under high hydrostatic pressures has been proofed in vertical as well as in horizontal large diameter boreholes. The knowledge required for the design and construction of flow barriers is available. Efficient large scale SVV seals may now be constructed in salt formations with low technical and financial effort. But, to proof the technical and functional feasibility particular studies (e. g. real scale sealing constructions) are required.

The BfS is currently working on adapting the construction engineering works for the sealing structures and the related safety demonstrations to the currently known information of the individual sealing locations in the Morsleben mine. Following this, it must be evaluated whether the entire safety case has to be adapted to new findings. That is the case when key assumptions relating to the sealing structures' system behaviour are no longer in compliance with the fundamentals of the safety case.

5 REFERENCES

[0] Gutsch, A.-W.; Preuss, J.; Mauke, R. (2009): Experimental results on salt concrete for barrier elements made of salt concrete in a repository for radioactive waste in a salt mine: Cementitious Materials in Safety Cases for Geological Repositories for Radioactive Waste: Role, Evolution and Interactions, OECD/NEA Workshop Proc., November 17-19, 2009, Brussels, Belgium

[1] Stahlmann, J.; Mauke, R.; Mohlfeld, M., Missal, C. (2013): Monitoring of Sealing Dams - Experiences from a Test Set-Up at the Repository ERAM, Germany: Monitoring in Geological Disposal of Radioactive Waste: 'Objectives, Strategies, Technologoies and Public Involvment', International Conference and Workshop, March 19-21, 2013, Luxembourg

[2] Mauke, R.; Mohlfeld, M. (2010): In situ Versuch für ein Abdichtungsbauwerk im Steinsalz – Zielstellung, Versuchsprogramm, geotechnische Instrumentierung: Mitteillungen des Instituts für Grundbau und Bodenmechanik TU Braunschweig, Messen in der Geotechnik,, Braunschweig, Germany

[3] Mauke, R.; Stahlmann, J.; Mohlfeld, M. (2012): In-situ verification of a drift seal system in rock salt – operating experience and preliminary results: Proceedings of the 7th Conference on the Mechanical Behaviour of Salt, April 2012, Paris

[4] Mauke, R. (2011): In Situ Investigation of the Morsleben Drift Seal – Operating Experience and Preliminary Results: Proc. 2nd US/German Workshop on Salt Repository Research, Design, and Operation, November 9–10, 2011, Peine, Germany, Report Sand 2012-1254, Sandia National Laboratories

[5] Mauke, R. (2012): In Situ Investigation of the Morsleben Drift Seal – Operating Experience and Preliminary Results: Proc. 3rd US/German Workshop on Salt Repository Research, Design, and Operation, October 8–11, 2012, Albuquerque, New Mexico, USA, Report Sand 2013-1231, Sandia National Laboratories

[6] Mauke, R. (2013): In Situ Investigation of the Morsleben Drift Seal – Operating Experience and Preliminary Results: Proc. 4th US/German Workshop on Salt Repository Research, Design, and Operation, September 17–18, 2013, Berlin, Germany, (Report in preperation)

[7] Rauche, H., at. al. (2004): Closure of the Morsleben Repository - Conceptual Design and Safety Proof of Shaft Sealing Systems: Disposal Technologies and Concepts 2004, International Conference on Radioactive Waste Disposal, April 26-28, 2004, Berlin, Germany

[8] Herbert, H.-J. (2000): Zur Geochemie und geochemischen Modellierung hochsalinarer Lösungen mineralischer Rohstoffe – Geol Jhb., Reihe D, Heft SD1, 191p.

[9] Meyer, Th. & Herbert, H.-J. (2007) Langzeitversuche zur Korrosion von Salzbeton durch salinare Lösungen – GRS-Z-2007 report for BfS, PSP Element 9M 232 200 11, 15 p.

[10] Herbert, H.-J., Hertes, U., Meyer, L., Hellwald, K., & Dittrich, J. (2011): Qualifizierung von Strömungsbarriere in Salzformationen - GRS-263, ISBN 978-3-939355-40-3, 201 p.

[11] Herbert, H.-J. (2007): Self Sealing Backfill (SVV) – A salt based material for constructing seals in salt mines. – Proceedings of the 6th Conference on the Mechanical Behaviour of Salt, 22-25. Mai 2007, Hannover.

[12] Herbert, H.-J.,Meyer, L. & Hertes, U. (2011): SVV a self-sealing material for technical barriers in salt mines – experimental results - Proceedings of the 7th Conference on the Mechanical Behaviour of Salt, April 2012, Paris, 8p.

[13] Herbert, H.-J., Meyer, Th., Schmidt-Döhl. (2003): Endlager Morsleben – Korrosion von Salzbeton durch salinare Lösungen. Bericht GRS - A - 3170, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig

[14] Meyer, Th., Schmidt-Döhl, F. & Herbert, H.-J. (2002): Endlager Morsleben – Zementkorrosion – GRS-A-3034, report for BfS, PSP Element 9M 232 200 11/12, 221.p.

[15] Hagemann, S. and Meyer Th, (2003): Unsicherheits- und Sensitivitätsanalyse zur Korrosion von Salzbeton durch salinare Lösungen - GRS-A-3458, Projekt Morsleben, PSP Element 9M 232 200 11, 114 p.

[16] Bonen, D. (1992): Composition and appearance of magnesium silicate hydrate and ist relation to deterioration of cement-based materials – J. Am. Ceram. Soc. (75), p 2904-2906

[17] Meyer, Th. & Herbert, H.-J. (2008): Modelltheoretische Untersuchung der Umlösekapazität von IP21-Lösung bei der Korrosion von Salzbeton – GRS-A-3384, Projekt Morsleben, PSP Element 9M 232 100 51, 36p.

[18] Niemeyer, M., Wilhhelm, St., Hagemann, S, Herbert, H.-J. Xie, M. (2012): Stillegung ERAM Zusammenfassende Auswertung von Experimenten und Modellrechnungen zur Korrosion von Salzbeton mit IP21-Lösung – AF Colenco4651/193, 66p.

[19] Herbert, H.-J. (2011): Verschlussbauwerke aus selbstverheilendem Salzversatz (SVV) – Kali und Steinsalz, Heft 1/2011, 42-50, Berlin, ISBN 1614-1210

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