
Final Results of the BAMBUS II Project – Experimental and Modelling Results concerning Salt Backfill Compaction and EDZ Evolution in a Spent Fuel Repository in Rock Salt Formations

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ABSTRACT: Within the framework of the BAMBUS-II (**B**ackfill and **M**aterial **B**ehaviour in **U**nderground **S**alt Repositories) project post-test investigations and modelling was performed to confirm and improve constitutive models used to predict the long-term evolution of backfill porosity and excavation disturbed zone (EDZ) in and around disposal drifts in a HLW repository in geological salt formations. Although significant deviations between measured and predicted data were observed during experiment conduction, post-test investigation of the compacted backfill as well as new calculations with improved 3D-models yielded satisfactory agreement between experimental and calculation results. Recently developed models applied to predict EDZ development after drift opening and its healing after backfill emplacement were found to represent measured EDZ generation data satisfactorily. The healing of the disturbed rock observed in situ, however, was not predicted adequately indicating further research need of this important long-term safety relevant rock behaviour.

1 INTRODUCTION

In the concepts for the disposal of radioactive waste in geological salt formations backfilling is an important component in the multi-barrier system. Backfilling with crushed salt remaining from excavation of underground disposal rooms is needed to stabilize the underground repository and to seal the waste from the biosphere. The concept for the direct disposal of spent nuclear fuel elements considers the emplacement of self-shielding Pollux-disposal casks in several parallel running underground drifts. Immediately after deposition of the casks the empty drift volume is backfilled.

To verify constitutive models used to predict the long-term safety relevant compaction of the salt backfill the “**T**hermal **S**imulation of **D**rift **E**mplacement (TSDE)” experiment was performed in the Asse mine in Germany. Post-test investigations included EDZ investigation in the TSDE test field. Both parts were combined in the BAMBUS-II project sponsored by the Commission of the European Communities (CEC).

The TSDE test field (Fig. 1) consisted of two 3.5-m-high and 4.5-m-wide and 70-m-long backfilled drifts. In each test drift, three simulated and electrically heated Pollux casks of 1.5 m diameter, 5.5 m length, and a mass of 65 Mg were deposited. The nominal heater power of each cask was 6,4 kW.

Heating was started in September 1990.

After five months, the maximum temperature of 210 °C was reached. In the following, the temperature decreased to 170 °C at the termination of the more than eight years long heating period (Fig. 2). This was due to the increase of thermal conductivity of the crushed salt backfill in consequence of the material compaction induced by drift convergence. Until the end of the heating period in February 1999, drift closure led to a reduction of backfill porosity from initially 35 % to 20,6 – 24,5 % in the different parts of the test drifts. The pressure built-up in the heated backfill ranges between 2 – 4 MPa .

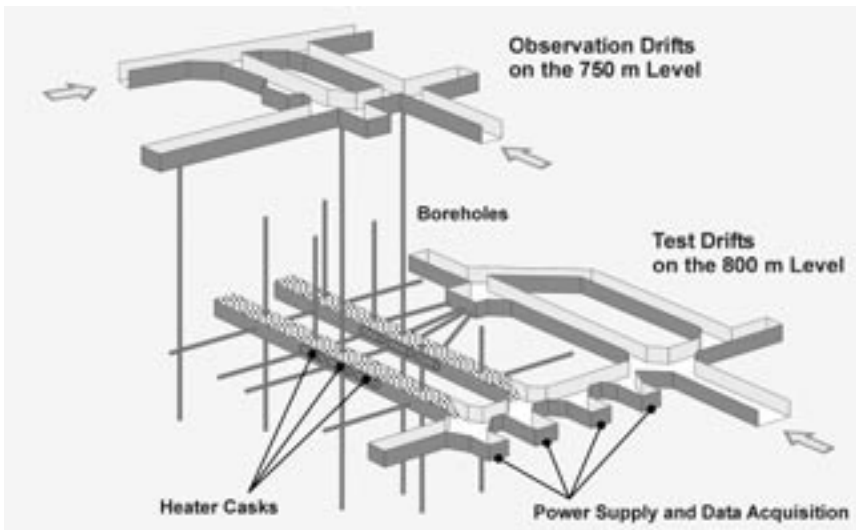


Figure 1: TSDE test field at 800-m level of Asse mine

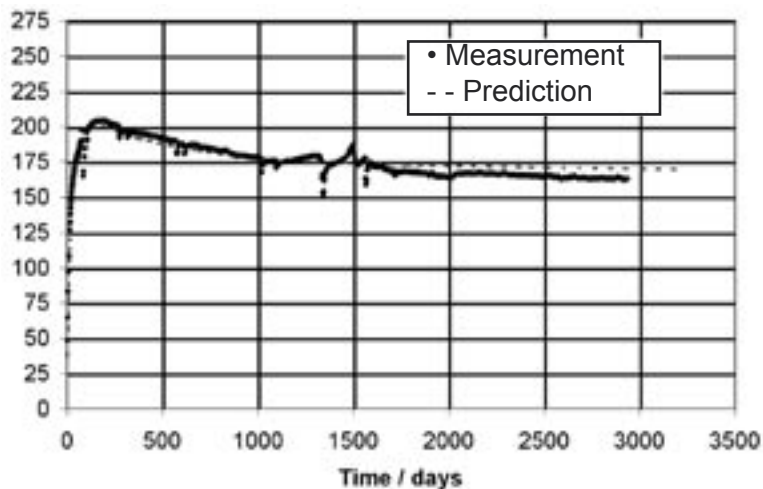


Figure 2: Temperature evolution at the central heater cask surface

Numerical predictions of backfill compaction and of the evolution of the EDZ in the host rock were performed by several project partners and compared to measuring results obtained during experiment conduction and in the post-test analysis phase.

During experiment conduction, predicted drift closure and porosity decrease data showed distinct overestimation in comparison to the measured data (Fig. 3). It has to be noted, however, that the measuring results had to be taken 3 m outside the test field centre because of the early failure of horizontal convergence measuring devices. Since these data do not adequately represent the situation in the central cross section because of the finite length of the test set-up, it was decided to uncover test drift B (Fig. 4) to enable post-test investigation of the remaining porosity distribution in the test field. The test field was uncovered in the years 2000 and 2001.

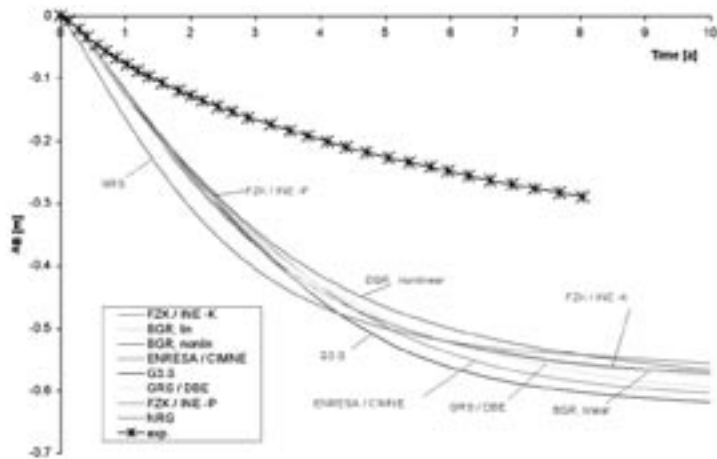


Figure 3: D-modelling results in comparison to measured drift closure data (Bechthold et al., 1999)

2 POST-TEST INVESTIGATION OF THE TSDE EXPERIMENT

2.1 Backfill Porosity

Samples of the compacted backfill material were taken at several cross sections (Figure 4) and analyzed in the laboratory (1).

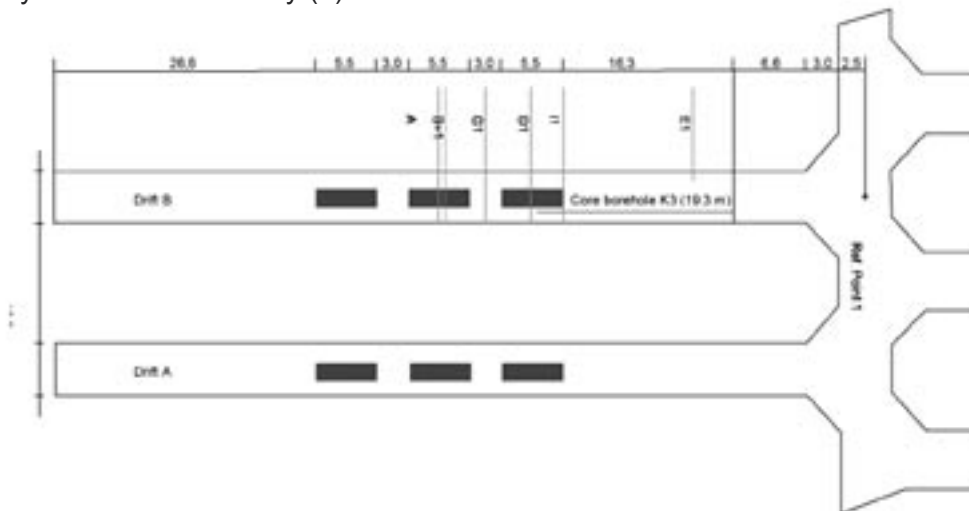
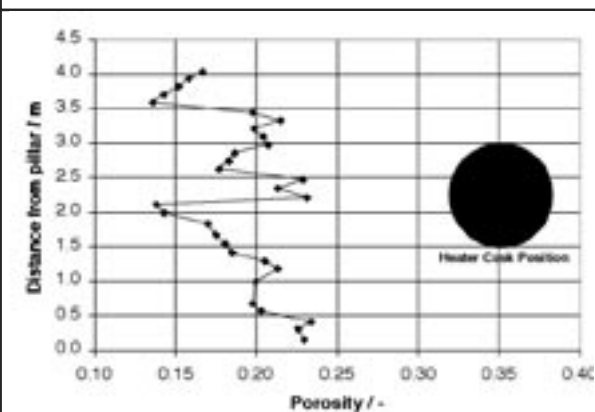


Figure 4: Sampling cross sections in the TSDE test field

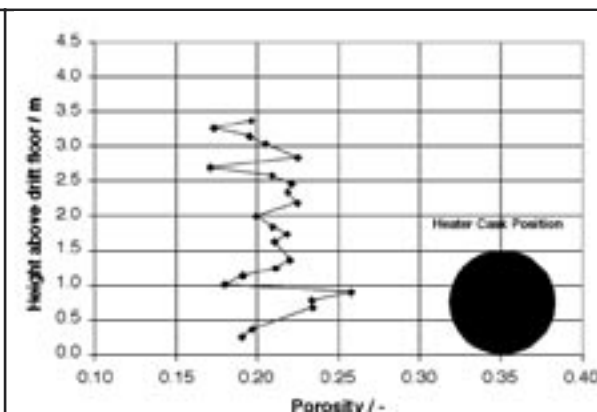
Of special interest was the situation in the central part of the test field at cross section B+1 where from the viewpoint of 2D-modelling adequate plane symmetry prevails. Here, complete vertical and horizontal profiles were analyzed for their remaining porosity (Fig. 5). Though significant variations can be seen along the profiles, the porosity decreases slightly towards the roof in case of the vertical profile and from the pillar towards the drift wall in case of the horizontal profile. Generally, the porosity in the centre of the test field is lowest with average porosities of about 0.2. In section 3 it will be shown that a porosity of 0.2 corresponding to a drift closure of about 0.37 m agrees fairly well with the results of improved 3D-models.



a) Sampling locations



b) Horizontal porosity distribution



c) Vertical porosity distribution

Fig. 5: Post-test investigations at TSDE cross section B+1

2.2 Excavation Disturbed Zone

It is known that deviatoric stress situations around underground disposal rooms may lead to the development of excavation disturbed zones, the permeability of which being significantly higher than that of the undisturbed rock. These zones represent potential pathways for radionuclides released from waste canisters. Hence, healing of these zones after the installation of geotechnical barriers or the emplacement of backfill material would be advantageous. Therefore, the permeability in the rock around the TSDE-test drifts was investigated at the end of the heating phase.

For the measurements, two boreholes, P3 and P4, with a diameter of 86 mm were drilled parallel to the walls of the northern and the southern test drifts, at distances of 1.5 m and 0.5 m, respectively (Fig. 6). Measurements were carried out both in the non-heated area and the heated area beside the test drifts. The measuring points were selected under consideration of a maximum packer temperature of the used probe of about 80°C. In borehole P3, measurements were performed at depths of 13 m at a temperature of 44°C and 27.75 m at a temperature of 71°C. In borehole P4, measuring points were at depths of 9.8 m at a temperature of 43°C and 27.5 m at a temperature of 80°C.

For the permeability measurements, a four-packer probe was used with a 0.8-m-long central test interval and two control intervals of 0.3 m length each at both sides of the test interval. The packers had a length of 0.4 m and were pressurized individually with hydraulic oil up to about 8 MPa. Test fluid was nitrogen.

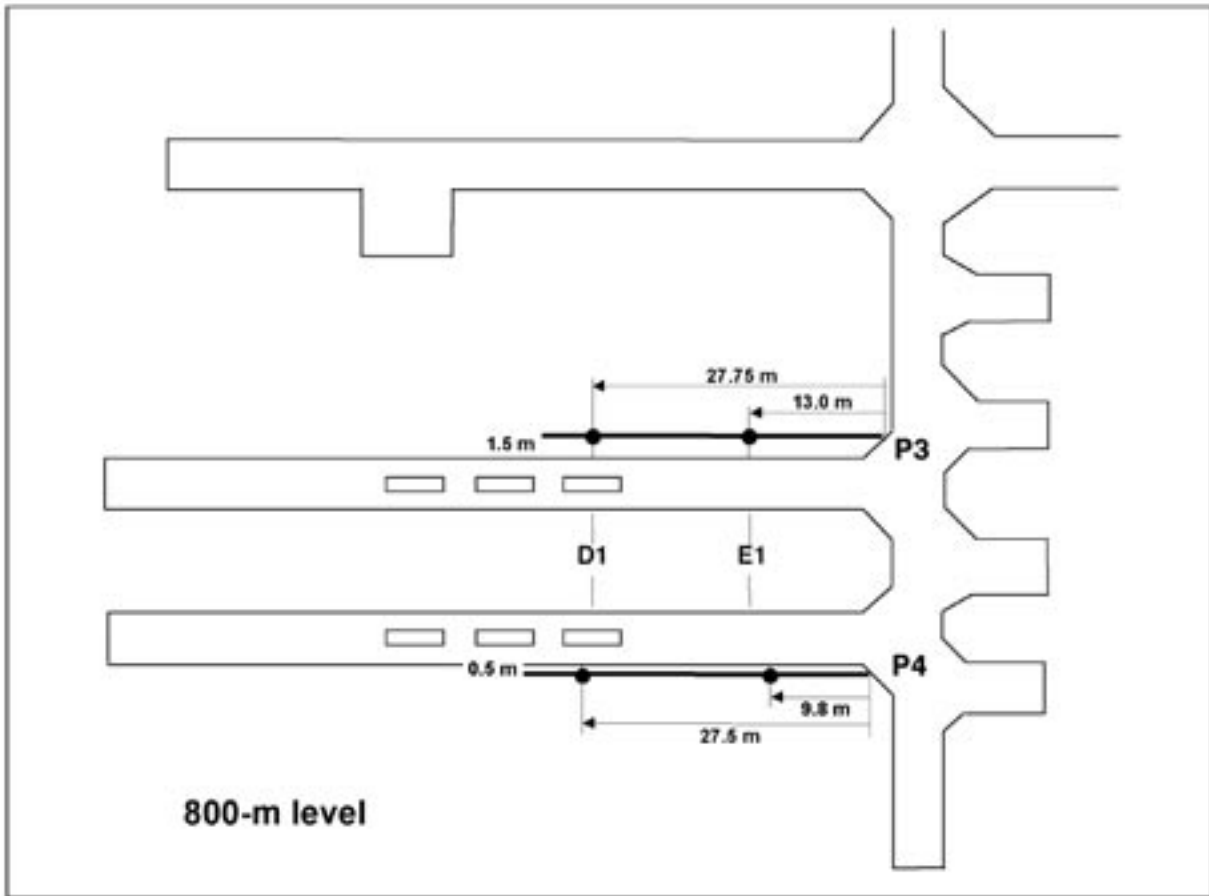


Figure 6: Location of permeability measurement boreholes in the TSDE test field.

Gas which was injected into the test interval with a maximum injection pressure between 1.6 and 2.1 MPa. Further details about the measuring equipment and the performance of permeability measurements are described in (2).

Because low permeability values were expected, pulse injection tests were performed in all cases. During the injection phase, a constant nitrogen gas flow of 500 to 550 ml/min was applied. During the injection phases, no measurable gas flow into the surrounding rock was detected. The following shut-in phases lasted up to fourteen days.

In Figure 7, one of the measured and calculated pressure decay curves is shown. The calculations were performed with the commercial code Weltest 200 (3) which was originally developed for oilfield reservoir engineering.

The calculations yield optimum formation parameters, among them permeability, on the basis of a chosen "reservoir model". The following model assumptions were made: (1) The formation is homogeneous and infinite and has a porosity of 0.2 %, (2) Partial water saturation in the pore space is neglected, and (3) The borehole has a finite radius and a respective storage capacity.

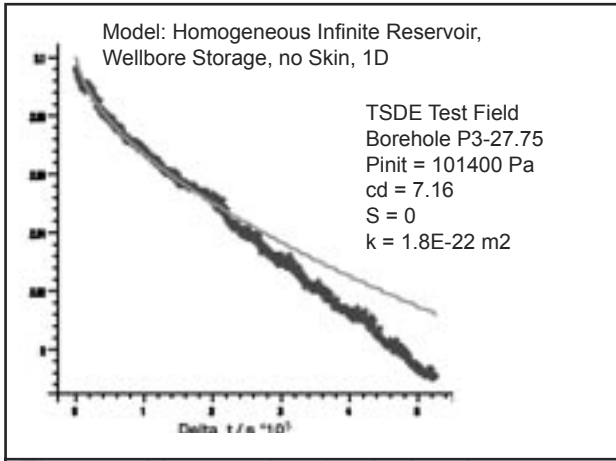


Figure 7: Measured and calculated pressure decay in borehole P3 at 27.75 m depth

All permeability values determined from the four measurements in the excavation disturbed zone were in the order of 10^{-22} m^2 . In all cases, the measured pressure decay rates showed a linear trend after some hours indicating that packer leakage rates were higher than gas flow rates into the surrounding rock. From this fact it can be concluded that real permeability values were even smaller than the determined values which represented the limit.

Permeability values of less than 10^{-22} m^2 correspond to non-disturbed rock salt, thus indicating that if an excavation disturbed zone had existed after drift excavation, it was healed during heating. Healing is also indicated by re crystallization of the rock salt in the heated area resulting in very large salt crystals which were observed in the cores from both boreholes.

However, the zone directly at the drift walls could not be examined in these tests. But during the post-test investigations after cool-down, respective tests were performed by the École Polytechnique–G.3S with a new designed measurement equipment (Figure 8) both in the middle of the heated zone and in the area undisturbed by the thermal load at the entrance of the test drift.

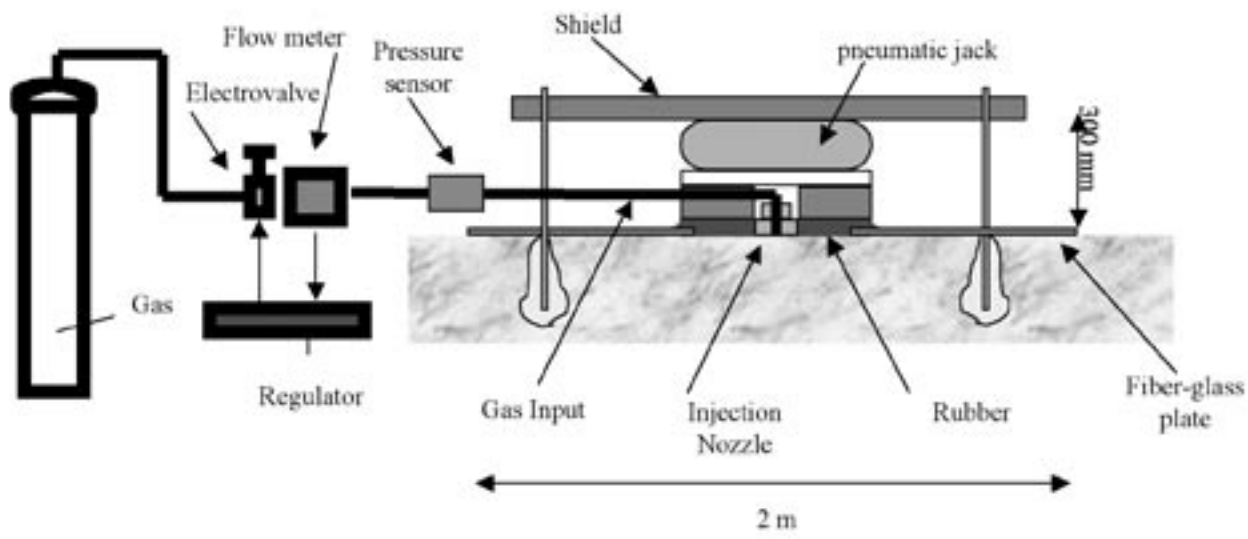


Figure 8: Conceptual design of the gas permeability test performed by G3S

The permeability of the rock mass to the gas can be deduced from the diffusion equation, assuming constant temperature, low gas pressure (<10 MPa) and Darcy flow:

$$\Delta P^2 - \frac{1}{\alpha} \frac{\partial P^2}{\partial t} = 0 \quad \alpha = \frac{k}{\mu \phi c_g}$$

Where: P is the gas pressure, k the intrinsic permeability, μ the gas viscosity, c_g the gas compressibility and ϕ the rock porosity.

In the case of transient flow, the diffusion equation cannot be solved analytically. Therefore, the permeability is assessed using the finite difference method by optimizing the experimental results using both porosity and permeability as control variables. The first experiment was carried out at the middle of the heated zone. The results (Figure 9) show a significant increase of the permeability ($k = 2 \cdot 10^{-15} \text{ m}^2$) compared to the typical value of 10^{-20} m^2 often admitted for undisturbed salt rock mass.

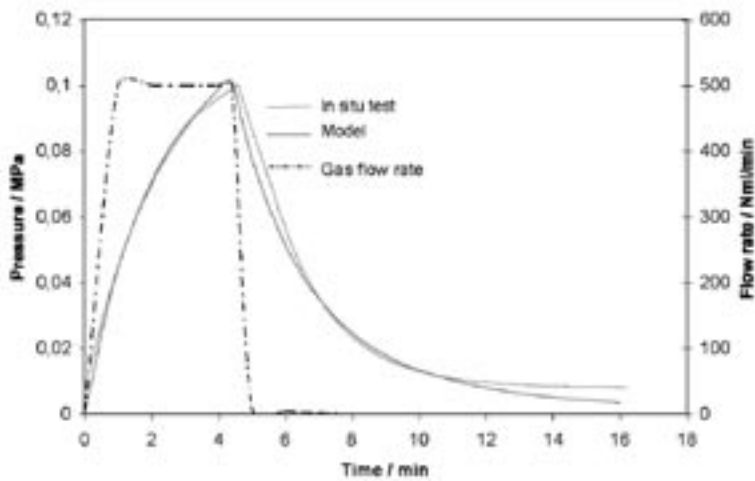


Figure 9: Gas permeability test in the heated area of the TSDE test field.

Comparison between in-situ data and numerical modelling data assuming a porosity of 0.15 and a permeability of $k = 2 \cdot 10^{-15} \text{ m}^2$

The results an important increase of the permeability in the heated area, which might lead to the conclusion that the EDZ is amplified due to the thermal loading. However, it is very likely that a significant part of the additional damage comes from the cooling phase. Indeed, the sudden interruption of the heating in the TSDE experiment may have induced tensile stresses leading to fracturing and growth of the initial EDZ around the drift. Since the decrease of the temperature would be much slower in an actual repository, such stresses should not develop.

3 MODELLING

3.1 Drift Closure/Backfill Compaction

As indicated and shown in the introduction, the drift closure or porosity decrease was significantly over predicted by the older 2-D thermo-mechanical analysis that was performed in a relatively small domain (6 to 7 times the drift size). This boundary was demonstrated to be insufficient both for temperatures and for field stresses. The long term duration of the test (10 years) requires a larger domain for the thermal problem to be solved and requires 3-D representation of other ventilated drifts. An advantage of the boundary being near the drift is that a smaller stress can be imposed (for instance 10 MPa instead of the more realistic 12 MPa). That preliminary model incorporated a thermal conductivity of the backfill dependent on porosity. However, since the temperature has an important effect on salt rock thermal conductivity the crushed salt thermal conductivity should be taken dependent on temperature and porosity. These types of models over predict temperatures, convergences and stresses because a 2-D approach is equivalent only to an infinite drift with a continuous heater.

Thus, an improved 3D-model was developed for the post-test analyses (Fig. 10). The model is 125 m in the vertical direction, 100 m in the horizontal direction (perpendicular to drifts) and 25 m in the axial direction. The model comprises 65954 nodal points and uses linear brick elements with selective integration (integration rule in order to correctly model incompressibility, which uses standard rule for the deviatoric part of strains and reduced rule for the volumetric part of strains). The mesh is practically uniform, except near the drifts where there are moderately distorted elements. Uniformity is an interesting property when iterative solvers are used. Previous meshes (using linear elements as well) with a more detailed drift and heater representation were disregarded due to numerical problems which did not permit the calculation to proceed.

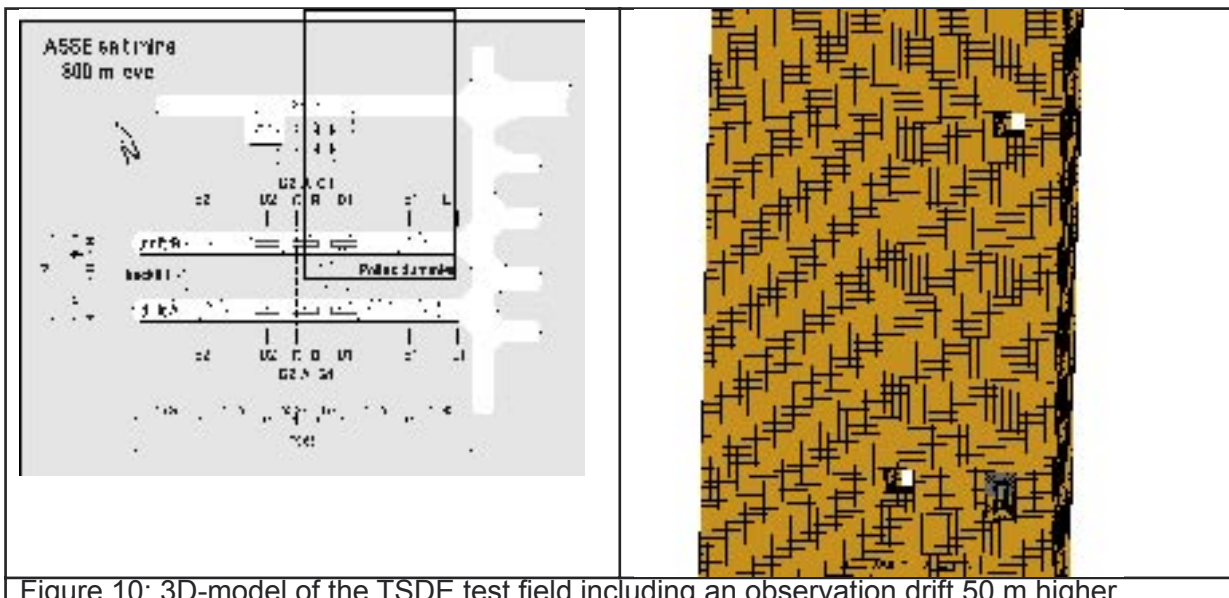


Figure 10: 3D-model of the TSDE test field including an observation drift 50 m higher

Stress relaxation during 1.5 years was imposed before initiating heating. One and a half heaters were considered in the model due to symmetry. All parameters were taken from the previously prepared specifications except the constitutive model for crushed salt, which was calibrated in the context of the preceding project phase BAMBUS I (4). This constitutive model is described in detail in (5). Figure 11 shows the calculated drift closure evolution which is now in excellent agreement with the measured data.

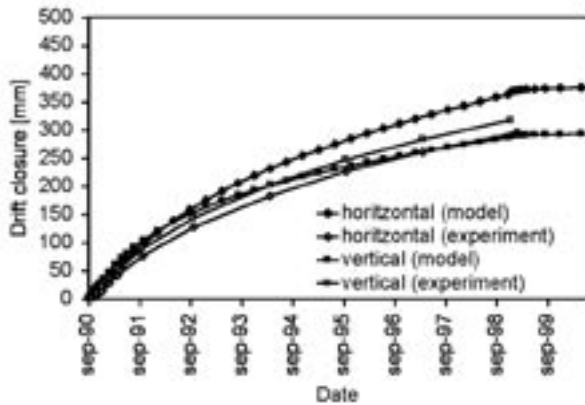


Figure 11: Drift closure in the heated part of the TSDE test field as calculated with an improved 3D-model

3.2 Excavation Disturbed Zone (EDZ)

A 2-D model has been used to simulate the mechanical behaviour (including dilatancy) around an underground cavity in rock salt. This analysis has been carried out with CODE_BRIGHT (6). The main objective of the calculations was to simulate the dilatancy properties of the rock. A relation between porosity and permeability based on in situ values was used. The calculations include creep deformation of the rock and backfill and the viscoplastic deformation in transient and non-isothermal conditions.

The model (two-dimensional) makes use of triangular quadratic elements (1033 elements and 2108 nodes) (Figure 12). Three materials have been considered: rock salt, backfill, and the steel canister emplaced in the drift.

A constant stress of 12 MPa and a temperature of 36.4 °C were assigned to the upper and right boundaries, whereas the bottom and left were fixed zero-displacements boundaries. A heat input of 19.61 J/s/m was assigned to the canister. Initial stress in the backfill was zero and its initial porosity was 0.31. Initial stress in the rock was -12 MPa (before excavation and heating) and its initial porosity was 0.001. The duration of the simulation was 3645 days, i.e. 10 years (Figure 13).

Initially, the porosity value in the rock was considered to be very low. In fact a residual porosity of 0.001 is normally present in the unconnected voids. When the analysis begins, porosity increases due to shear-stress induced dilatancy, especially near the cavity. The highest values were registered in the walls, close to the roof of the drifts. The maximum porosity, a bit higher than 0.025, was calculated in the upper part of the pillar wall between cavities, after 600 days of simulation. Later, due to the progressive drift closure and backfill pressure increase, porosity values decreased at all locations. After 3500 days, the porosity reached 0.005 to 0.015. While the backfill compacts (positive volumetric deformation), the rock near the drift wall expands (negative volumetric strain).

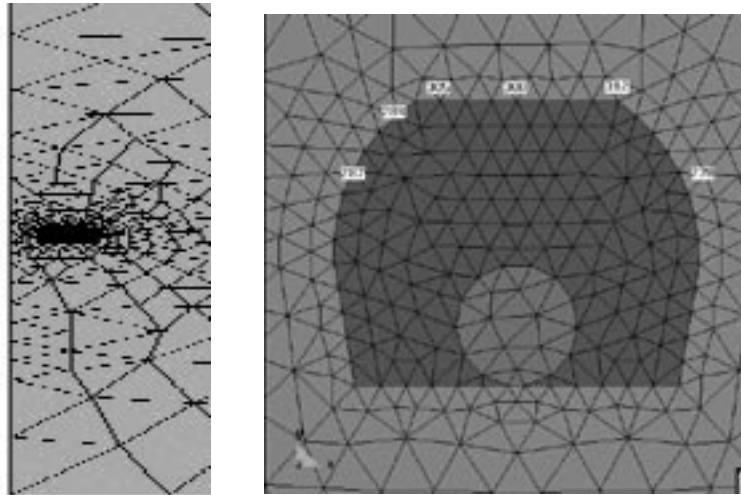


Figure 12: View of the finite element mesh used in the analyses and detail of the drift area.

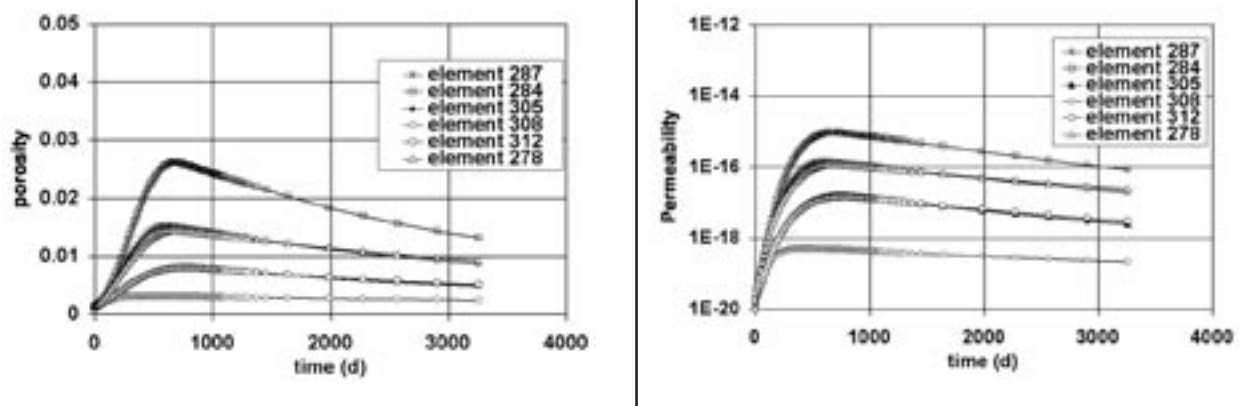


Figure 13: Time evolution of porosity (left) and permeability (right) in the rock around the opening for elements near drift wall. Location of elements for evolution plots see Fig. 12 right).

One of the objectives of the investigation of the EDZ was to predict its permeability. To achieve this objective a power law was used that expresses permeability as a function of the initial permeability, initial porosity, and the current porosity of the rock. This law neglects anisotropy effect, which could be incorporated later. The mathematical expression is as follows:

$$k = k_0 \frac{\phi^n}{\phi_0^n}$$

where k is intrinsic permeability, ϕ is porosity, and n is the power of porosity.

Considering an initial value of permeability of $k_0 = 10^{-20}$ m² and an initial porosity of $\phi_0 = 0.001$, and the power of $n = 3.5$, the mathematical expression becomes:

$$k = 10^{-21} \frac{\phi^{3.5}}{0.001^{3.5}} = 3.2 \times 10^{-11} \phi^{3.5}$$

Permeability in the EDZ has been calculated using this law and is plotted in Figure 14 as well. For a porosity of 0.027 a value of 10^{-15} m² is obtained. These values of permeability are in agreement with

those obtained in the Asse mine through gas flow tests. The results are presented for 0, 250, 1000, 1500, 2000, 2500 and 3000 days of simulation. It should be observed that from 0 to approximately 1000 days, permeability increases, reaching a value near 10^{-15} m^2 . Subsequently, it reduces due to the confinement effect of the backfill.

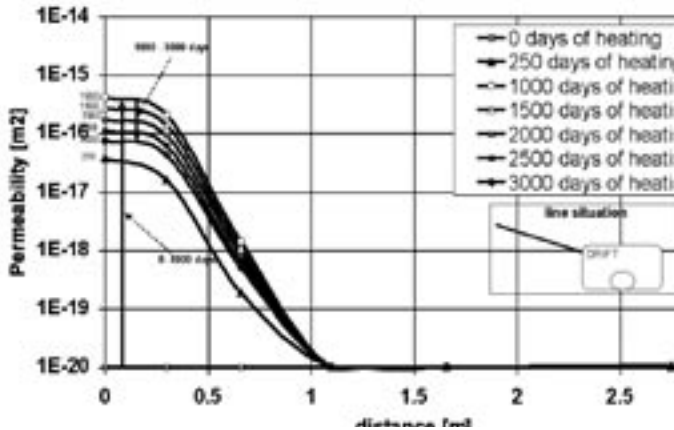


Figure 14: Evolution of permeability into the rock for several times.

Permeability decreases and the values (next to the drift wall) are about 10^{-16} - 10^{-17} m^2 . The initial condition was not recovered after 10 years of simulation. This is contradictory to the permeability measurements performed at the end of the heating phase which yielded values of 10^{-22} m^2 . Obviously, the healing of the EDZ is not adequately represented by the model thus indicating the need for further model improvement.

In conclusion, the permeability increase resulting from dilatancy is compensated by permeability reduction (creep compaction) in the present case. In fact, dilatancy is only active during the first 2-3 years. Later, shear stress decreases and mean stress increases and hence dilatancy disappears. When dilatancy is no longer active, permeability reductions take place by volumetric creep compaction.

4 SUMMARY AND CONCLUSIONS

A large-scale simulation experiment on the direct disposal of Spent Fuel in geological salt formations was performed in the Asse mine in Germany from September 1990 until February 1999. Main Objective of this experiment was to investigate the coupled hydro-thermo-mechanical behaviour of the host rock and the crushed salt backfill in the simulated disposal drift. Backfill compaction and evolution of the excavation disturbed zone in the rock around the test drift was in the foreground of post-test investigations performed to confirm the test data obtained during almost nine years of experiment conduction. Confirmed test data were compared with data of numerical simulations to evaluate the capability of numerical models used to predict long-term system behaviour.

Regarding backfill compaction in the test drift it was found that 3D-modelling is needed to satisfactorily simulate the conditions in the drift of limited length and thus to obtain satisfactory agreement between experimental and numerical results. Older 2D-models were able to predict measured data only in the centre of the test field where plain symmetry prevails.

EDZ evolution was analyzed by prediction of dilatancy in the rock around the drift with a 2D-model. The calculation data are reasonable regarding EDZ generation, but healing of EDZ, as measured in the test field, was not predicted adequately. Hence, further model development is needed to improve adequate simulation of this very important long-term rock behaviour.

5 ACKNOWLEDGEMENTS

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