

HYDRAULIC INVESTIGATION OF THE EXCAVATION DISTURBED ZONE AROUND DRIFTS IN ROCK SALT

Johannes Droste, Klaus Wieczorek, Ulrich Zimmer
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
D-38122 Braunschweig

ABSTRACT

An important feature of the multi-barrier concept for final disposal of nuclear waste is the sealing of drifts by bulkheads. The effectiveness of bulkheads is strongly dependent on their coupling to the rock and on the integrity of the rock formation.

Rock salt is a favorite formation type for a nuclear waste repository in the German disposal concept. It is known that excavation disturbed zones (EDZ) develop during the excavation of drifts and chambers in rock salt. The extent and the hydraulic properties of an EDZ were investigated in an experiment performed in the Asse salt mine near Braunschweig, Germany.

Both gas and liquid flow through the EDZ were investigated by injection tests with nitrogen and salt brine, respectively. The tests were performed in vertical boreholes at various depths below the floor. From the results of the gas injection tests, an extension of the EDZ in the range of 1.5 m beneath the drift floor was derived. The permeability outside the EDZ was found to be below 10^{-21} m^2 , while at 1 m depth below the drift floor a permeability of about 10^{-17} m^2 was measured.

The liquid injection borehole was used to perform impregnation tests with saturated salt brine. Electrodes for geoelectric measurements were placed in additional boreholes surrounding the liquid injection borehole and on the drift floor. The geoelectric measurements were used for the determination of the distribution of the specific electric conductivity of the rock which is closely dependent on its brine content. Thus, these measurements could be used for tracking the brine spreading into the rock. In agreement with the gas injection tests, the liquid injection tests showed that no significant impregnation of the rock was possible at depths of 2 m and below, while a total amount of 7.5 l of brine was injected at 1 m below the floor. The geoelectric measurements, however, indicated that the brine did not spread evenly into the surrounding pore space, but more likely flowed along a flowpath. This interpretation was confirmed afterwards by overcoring of the liquid injection borehole. A sulfatic layer was identified as the suspected flowpath.

Mechanical modeling was performed in order to compare the results of the hydraulic measurements to the stress field. The extension of the EDZ as determined by the injection tests correlated with a zone of low least principal stress which is a prerequisite for dilatancy.

Main task of a follow-up program is the investigation of the healing of the EDZ with time after emplacing a supporting backfill or bulkhead.

INTRODUCTION

The main advantage of the disposal concept of both nuclear and chemical wastes in underground repositories is the fact that the element transport in the lithosphere takes place in a geologic time scale. Prerequisite for this is the safe inclusion of the waste in the host formation. In order to assure safe inclusion, the multi-barrier concept was developed. Besides the geologic barrier, it incorporates engineered barriers like borehole seals, bulkheads, and shaft seals. The effectiveness of such seals is governed by their coupling to and by the integrity of the adjacent host rock.

Rock salt is a favorite formation type for a nuclear waste repository in the German disposal concept. From various investigations both in the bedded salt at the WIPP site (1, 2) and in German domal salt (3) it is known that excavation disturbed zones (EDZ) develop during the excavation of drifts and chambers in rock salt. While the formation of the EDZ can easily be detected by acoustic measurements, such measurements yield no information about the change in its hydraulic properties. These are determined by packer tests in boreholes. Such tests in the highly water-saturated rock salt at the WIPP site lead Stormont et al. (4) to the conclusion that the EDZ can be divided into a more disturbed zone where microfracturing and dilatancy occurs (leading to an increase in permeability) and a less disturbed zone which is characterized by a decrease of pore pressure. In the relatively dry domal salt of northern Germany, the EDZ reduces to the dilatant zone, but only little information on the change in hydraulic properties (3) has been gathered so far.

The extent and the hydraulic behavior of the excavation disturbed zone were the subject of the project ALOHA ("Untersuchungen zur Auflockerungszone um Hohlräume im Steinsalzgebirge") carried out at the Asse salt mine near Braunschweig, Germany. Main issue of a follow-up program is the healing of the EDZ with time after emplacing a supporting backfill or bulkhead. This paper presents the objectives, the experimental program, and the results obtained up to now.

OBJECTIVES

The objectives of the ALOHA project are

- the characterization of the EDZ with respect to its hydraulic behavior in terms of permeability, porosity, relative permeabilities, and capillary pressure,
- the investigation of the spatial extent of the EDZ,
- the investigation of the development of the EDZ with time, especially its healing after the emplacement of a supporting structure in the excavation.

The last objective is especially important for the long-term safety assessment, as it determines for what time the EDZ has to be taken into account. It cannot be investigated directly, however, since the time span for healing will be too long. As healing is a stress driven process, it is planned to derive a relation between stress and permeability. So, another objective is

- the derivation of a relation between stress and a permeability range which abstracts from structural properties of the salt and can be used as input for safety assessment calculations.

EXPERIMENTAL PROGRAM

The ALOHA phase 1 concentrated on the investigation of the hydraulic properties and the spatial extent of the EDZ. The experimental program included several in-situ investigations which were backed by laboratory testing and modeling. The in-situ measurements are

- measurement of the rock salt permeability by gas injection at different distances from a drift,
- injection of liquid (salt brine) into the rock salt, and
- tracking of the brine spreading by geoelectric measurements.

The investigations were performed in a 10-year-old test field on the 875-m level of the Asse salt mine near Braunschweig, Germany. An overview of the test arrangement is given in Figure 1. Two vertical boreholes in the drift floor (GI and FI) were used for injection testing with gas and liquid, respectively. The liquid injection borehole FI is surrounded by five additional boreholes (E1 - E5) which contain the cemented electrodes for the geoelectric measurements (see Figure 1). More electrodes are arranged in three profiles on the drift floor.

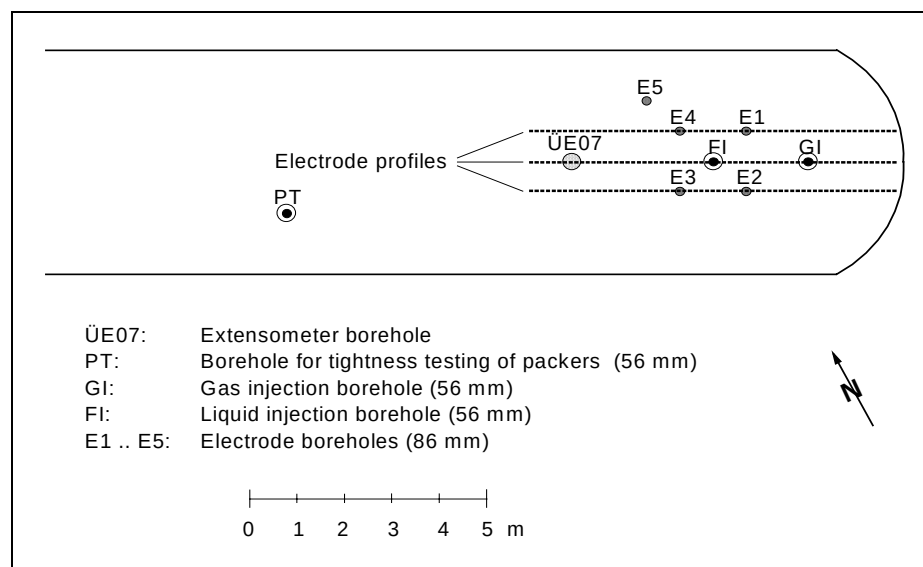


Fig. 1 Plan view of the test drift in the Asse salt mine

Additional gas injection tests were performed in a horizontal borehole in a pillar between two drifts on the 800-m level of the Asse mine.

Lab tests were aimed at the determination of two-phase flow parameters (relative permeabilities, capillary pressure) of rock salt which cannot be determined in situ, but are important for flow processes in partially saturated rocks.

Modeling comprised hydraulic design calculations and mechanical finite element calculations for comparison between the results of the permeability measurements and the stress state.

During the ALOHA phase 2, additional gas injection tests will be performed in the vicinity of various excavations with different sizes and symmetries. They will be coupled to the respective stress states by stress measurements and mechanical modeling. An especially interesting test site is located on the 700-m level of the Asse mine where a cast steel bulkhead was placed in a drift during the 1920's. Here, a partial healing of the EDZ might have taken place.

EXTENT AND HYDRAULIC PROPERTIES OF THE EDZ

In this section, the results obtained from in-situ testing in the drift on the 875-m level of the Asse mine are presented.

Gas Injection Tests

For gas injection testing, a part of a borehole, the test interval, is sealed off by packers. Gas is injected into the test interval and the pressure development during the injection phase and the subsequent shut-in phase is recorded. From the flow rate and the pressure curve, the permeability of the rock is derived.

For the tests, a four-packer probe with a diameter of 50 mm was used. The four sealing elements have a length of 500 mm each and are pressurized with hydraulic oil up to about 8 MPa. The central test interval has a length of 800 mm; two observation intervals of 300 mm length each are located above and below. For testing at low borehole depths, the upper observation interval was used as test (i.e., injection) interval. Test fluid was nitrogen; the maximum injection pressure was 3 MPa (for the measurements at 2 m depth and below) and 2 MPa (for the measurements at lower depths), respectively. The flow rate was in the range of 500 to 550 ml/min in all tests. For measurement and recording of the data, a PC-based 10-channel recording unit with flowmeters and pressure transducers was used.

Prior to the measurements, the probe was placed in a steel tube and an injection test was performed to determine the tightness of the measuring system. This is especially important when testing low permeability formations where only little gas flow into the rock can be expected.

Figure 2 shows the pressure development during the shut-in phases of the gas injection tests performed at different depths in borehole GI (see Figure 1). It can be seen that at depths of 2 m and below pressure decrease is very slow, which can be directly related to a small permeability, while at 1 m and 1.25 m depth, the rather quick pressure decay implies an increased permeability. The measurement at 1.5 m indicates a transition zone.

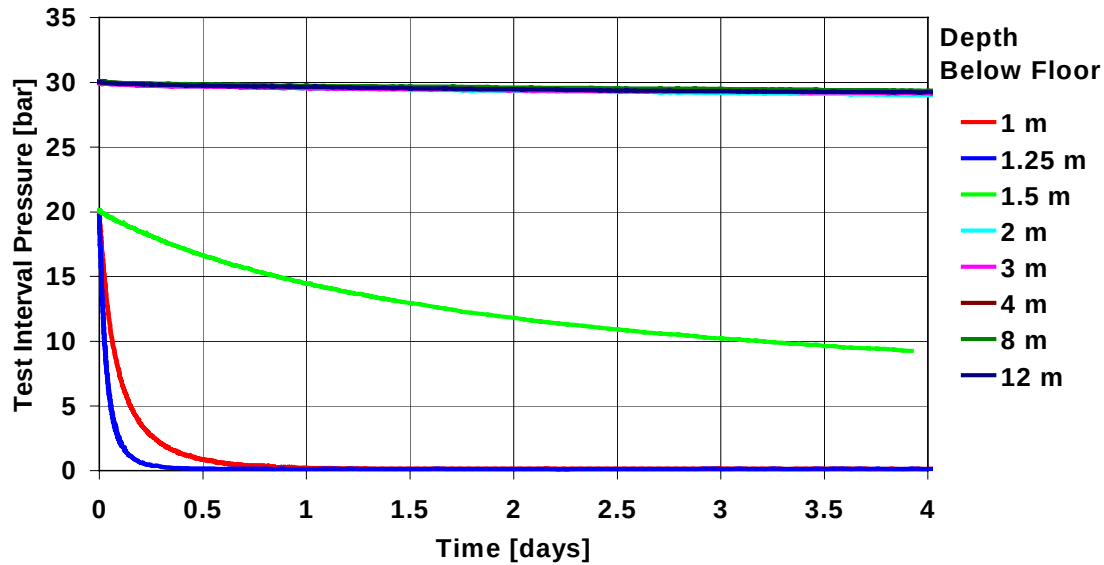


Fig. 2 Pressure development during the shut-in phases of the gas injection tests

The gas injection tests were evaluated using the commercial code Weltest 200 (5) which was originally developed for oilfield testing. It optimizes the certain formation parameters, especially permeability, on the basis of a chosen "reservoir model". The following assumptions were made:

- The formation is homogeneous and unlimited and has a porosity of 0.2 %.
- Partial water saturation is neglected.
- The borehole has a finite radius (0.56 mm) and a storage capacity according to the test interval volume.

Depending on whether the flow into the formation is regarded as one-dimensional (horizontal) or two-dimensional (with upward and downward components), different permeability values are obtained. The results are summarized in Figure 3 which shows the permeability results at different depths below the floor. The height of the rectangles in the figure is given by the test interval length, while the width is determined by the range of permeability.

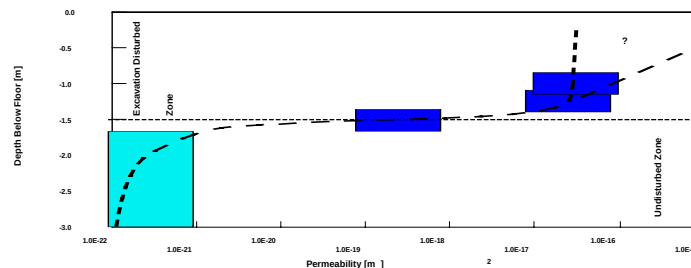


Fig. 3 Permeability distribution in the first 3 m below the drift floor

A sharp transition from the undisturbed to the disturbed zone can be seen at about 1.5 m depth. The permeability below is in the range of 10^{-21} m^2 or lower, while in the disturbed zone permeabilities around 10^{-17} m^2 are obtained. No information is available of the first 0.8 m below the floor which is due to the finite length of the sealing elements of the packer. Effort will be made in the second phase of the project to develop a measuring system for injection testing in the immediate vicinity of excavations.

Additional gas injection tests in a horizontal borehole showed that the extent of the EDZ is less than 1 m from the drift wall, in contrast to 1.5 m below the floor.

Liquid Injection Tests

Liquid injection tests with saturated salt brine were performed in borehole FI (see Figure 1) at depths of 1 m, 2 m, and 20 m below the floor. The packer probe used was similar to the gas injection probe. Injection was done by a pump with rates ranging between 0.4 and 0.8 l/h.

While at 2 m and at 20 m borehole depth no significant amount of brine could be injected into the formation (at a maximum injection pressure of 6 MPa), a total of 7.5 l of brine were injected at 1 m depth during two injection phases. The maximum injection pressure was 1.5 MPa. The second injection phase was evaluated in terms of permeability to brine using Weltest. The resulting value of 10^{-14} m^2 is much higher than the permeability to gas found in borehole GI at the same depth. The geoelectric measurements (see below), however, showed that the brine did not spread evenly into the pore space, but followed a preferential pathway. To clear this issue, the liquid injection borehole was overcored with a diameter of 400 mm and the core was inspected. The presumed pathway was found to be a sulfatic layer of several millimetres thickness.

To improve the comparability between the gas and the liquid injection tests, an additional liquid injection was performed in the gas injection borehole GI at 1 m depth. The permeability to brine evaluated from this test was in the range of 10^{-17} m^2 and thus in the same range as the gas permeability.

Generally, it can be stated that the liquid injection tests confirmed the results of the gas injection tests regarding extent and permeability of the EDZ. They also showed that the permeability variation in the EDZ may be high due to rock salt impurities.

Geoelectric measurements

The liquid injection tests were accompanied by geoelectric measurements which can be used to determine the electric resistivity distribution in the rock by injecting a current by a pair of electrodes and measuring the resulting potential differences between other pairs of electrodes. The resistivity is correlated to the moisture content of the rock salt. The correlation function is known from numerous laboratory tests (6, 7).

As expected, no changes in the resistivity distribution were found during the liquid injection tests at 2 m and at 20 m depth. A different result is obtained after the injection tests at 1 m depth. Figure 4 shows the resistivity distribution in the planes between the electrode boreholes. The cross line in the center shows the location of the injection borehole.

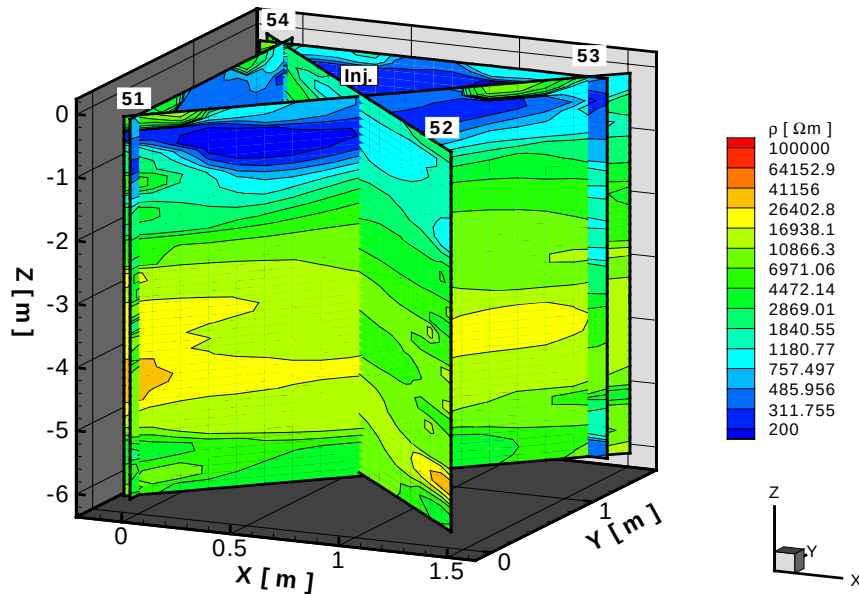


Fig. 4 Distribution of electric resistivity in the planes between the electrode boreholes after liquid injection at 1 m depth

It can be seen that the resistivity around 1 m depth is significantly lower than usual. The value of 200 to 1000 Ωm represents a water content of 0.3 to 0.5 % by volume. It is, however, also observable that the resistivity in the direction 51-53 is much lower than in the perpendicular direction 52-54 (see Figure 4). This is a hint for the uneven spreading of the brine by a pathway which has already been discussed above.

COUPLING BETWEEN HYDRAULIC PROPERTIES AND MECHANICAL STATE

The reason for the permeability increase in the EDZ is the dilatant behavior of the rock salt which occurs at certain stress states, as they are given near an excavation. Several dilatancy criterions were proposed by different authors:

$$\sqrt{J_2} \geq 0.83 \cdot \sigma_m + 19 \quad \text{Spiers et al. (8)}$$

$$\sqrt{J_2} \geq 0.81 \cdot \sigma_m \quad \text{Ratigan et al. (9)}$$

$$\sqrt{\frac{2}{3} \cdot J_2} \geq 0.86 \cdot \sigma_m - 0.0168 \cdot \sigma_m^2 \quad \text{Hunsche (10)}$$

with σ_m being the mean stress and J_2 the second stress invariant, defined as $J_2 = \frac{1}{6} \cdot ((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)$.

All equations show that a high difference between the principal stress components σ_1 , σ_2 , σ_3 (i.e., a high deviatoric stress) is a prerequisite for dilatancy. In order to compare the results of the permeability tests to the stress state of the salt rock around the excavation, mechanical modeling was performed using the finite element code ANSYS (11). An axisymmetric model of the drift and an injection borehole were considered sufficient. The model consisted of a sphere with a radius of 100 m containing 611 elements with 1940 nodes. The actual history of drift and borehole excavation was taken into account. The initial stress state (prior to excavation) was assumed as 14 MPa at the level of the drift floor and changing upward and downward according to the rock salt density of 2180 kg/m³.

The rock salt was modelled as elastic-viscoplastic material. The viscoplastic part included just secondary creep following the equation

$$\dot{\epsilon} = A \cdot \sigma^5 \cdot \exp\left(-\frac{Q}{R \cdot T}\right)$$

with the creep $\dot{\epsilon}$, a structural parameter A , the effective stress σ , the activation energy Q , the gas constant R and the absolute temperature T .

As a result of modeling, Figure 5 shows the distribution of least principal stress around the drift at the end of the calculation period. The drift height is about 2 m, the radius 2.25 m.

The least principal stress was chosen, because a low least principle stress implies a high deviatoric stress (and thus dilatancy). Several conclusions can be drawn from the figure:

- A small zone of tensile stress exists in the floor.
- A zone of strongly diminished least principal stress (down to 1.5 MPa) extends about 1.5 m into the floor.
- The extent of this zone into the wall is only about 0.5 m.

These results are in good agreement with the permeability tests. Especially the smaller extent of the EDZ into the wall in comparison to the floor is well reproduced.

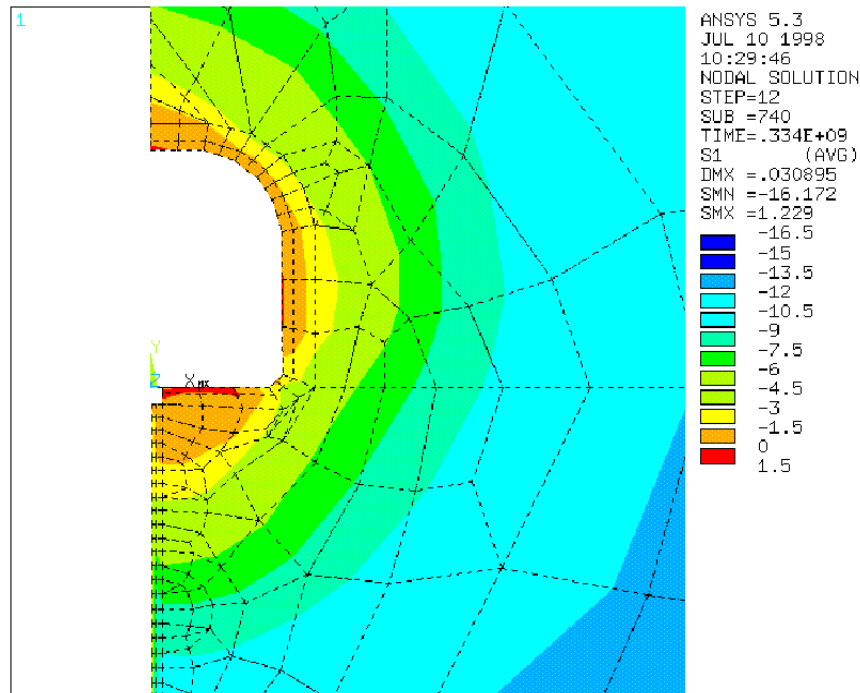


Fig. 5 Calculated least principal stress in the vicinity of the drift and the upper 5 m of the gas injection borehole at the end of testing

Further evaluation of the modeling results (e.g., in terms of where a dilatancy criterion is fulfilled) is not performed, since this modeling lacks reliable measurements of the initial stress state. More concise mechanical modeling, coupled to stress measurements, will be performed in the ALOHA phase 2.

OUTLOOK

Future investigations in the frame of the ALOHA project will concentrate on the relation between stress state and hydraulic behavior in order to predict healing of the EDZ. Therefore, various sites covering drifts as well as large chambers have been chosen for investigation. A site of special interest is a 70-year-old cast steel bulkhead in the Asse mine.

Laboratory investigations on intact, disturbed, and possibly healed salt samples and modeling with new codes that can take into account dilatancy will be performed in cooperation with the Sandia National Laboratories.

An additional objective is the development of a special equipment for permeability measurements in the very vicinity of openings (distances less than 0.5 m).

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