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Numerical and laboratory investigations of thermally induced fractures in rock salt

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Abstract. In order to widen the basis for the dimensioning of storage caverns in rock salt, some special attention must be paid to the temperature developments within the cavity during its operation. Passed numerical investigations have shown that a temperature change in the storage medium, such as natural gas or hydrogen, can cause stress differences of several MPa in the rock mass surrounding the cavern. If, as a result, the difference between horizontal and vertical stresses is increased, the rock being additionally loaded by a fluid pressure can fracture orthogonally to the lowest principal stress. The knowledge of temperature conditions and heat flows in the cavern surrounding salt rock are therefore of great importance. A wide variety of factors must be considered when investigating such mechanisms. The novel test facility at the Institute of Geotechnical Engineering of the Leibniz University Hannover is used to simulate the situation that occurs at the caverns edge when storage medium is withdrawn. This means, the cooling and the gas pressure inside the cavity are reconstructed on hollow cylindrical test samples made of rock salt from various locations to draw conclusions about the propagation of fractures and thus the safety of salt caverns under gas-loading. Before inducing any mechanical loads by means of a triaxial cell, a comprehensive investigation of the temperature field, resulting from the locally limited, artificially induced cooling of a sample is carried out with the new testing facility. While local temperatures in the sample drop by about 20 Kelvin, it is free to contract inwards, causing thermal stresses to decrease significantly. Therefore, the facility needs to be optimized and the testing scheme is changed. Instead of reducing stresses thermally, one of the mechanical loadings is diminished while the gas pressure inside the borehole is kept constant. As a result, the material visibly fractures while mechanical loadings are at a fully-compressive state.

1. Introduction

Until today, a common dimensioning basis for gas-filled caverns in salt rock mass does not exist, further investigations – especially considering the probable storage of hydrogen in the future - are required. For this reason, an important question has to be answered: How does rock salt react on temperature changes and gas pressure in combination? For the safety of salt caverns it is important to have the ability to estimate well the impact of temperature changes like they do happen in such cavities while being used. Especially during the gas-withdrawal phase the resulting temperature reduction can lead to significant changes in the stress level. Considering the properties of rock salt and the way they are described mathematically, several degrees of temperature change at the cavern wall can cause the stresses in the surrounding rock mass to change by several MPa. Large differences between such mechanical stresses and the internal gas pressure can cause infiltration-fractures at the cavern wall. For this reason, the Institute of Geotechnical Engineering in Hannover developed a facility, which not only simulates a gas pressure through nitrogen but also recreates the thermal processes resulting from locally limited temperature impacts in salt rock samples, focusing on the analogies to caverns during the withdrawal of gas.

2. Effective Stresses in Rocks

It has been known for some time that the effective stresses must exceed the fracture criterion in order to cause infiltration-fractures in the rock salt mass [1]. While the absolute stresses in a non-saturated body correspond to its effective stresses, an existing pore pressure absorbs loadings proportionally. If a mechanical load is reduced while pore pressure is constant, the stresses inside the grain matrix are shifted and cracks can occur. The prerequisite for such a mechanism is the presence of a fluid. Terzaghi [2] and Biot [3] formulated this mathematically in the middle of the 20th century:

$$\sigma_{eff}=\sigma_{tot}-\alpha * p_{fl} \tag{1}$$

It creates a connection between the forces in the grain matrix and the outer mechanical loading (σ_{tot} $\triangleq$ total stress). The forces actually acting on the salt grains (σ_{eff} $\triangleq$ effective stress) result from the difference between the mechanical load and the pore pressure (p_{fl}), whereby a material-specific reduction in the pore pressure is taken into account by the Biot-coefficient α. The aim of this research is therefore to investigate possible reasons for reductions of mechanical stresses in the grain structure and to verify this criterion laboratorily. Thermal processes are particularly considered, since temperature reductions contribute significantly to the stress decreases within a body.

3. Preliminary Tests

3.1. Working Principle of the New Testing Facility

The general idea of the recently manufactured testing facility [4] is to cool down a rock salt specimen, locally limiting the temperature decrease to a small area inside the borehole of a hollow cylinder. While the samples outer boundaries are constantly heated, a temperature gradient develops (Figure 1). Simultaneously, nitrogen can be injected from the bottom into the borehole of the sample, producing an inner fluid pressure.

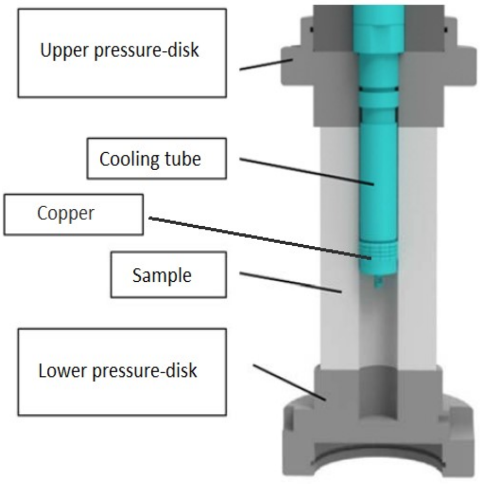

Figure 1. Experimental setup scheme

The testing-gadget is construed to include mechanical loads in further experiments. Therefore, the cooling-shaft passes through a pressure-disk at the specimen's top. At the end of the tube, which is being streamed through by a refrigerant, lies a copper extension. The idea is to induce cold temperatures at the sample's middle by means of a thermally well-conductive material. It is expected, that the developing gradient between inner and outer temperature causes large stress differences inside the rock salt and thus represents processes as they occur in salt caverns.

Depending on the outer forces and restraints as well as the temperature differences inside the tested body, vertical stresses can become tensile or at least significantly in amount lower than horizontal stresses - eventually causing the material to fracture in the horizontal direction. It is also possible that circumferential stresses exceed the vertical components or even become tensile, leading to vertical cracking.

Considering the recent findings, that with the infiltration of gases cracks in rock salt seem to occur at stress differences in the range of the rock salts tensile strength [5], it is not required to reach absolute tensile stresses in the specimen for fracturing under these conditions. In advance to any experiments straining the specimen with mechanical loads including inner gas pressure and thus making fracturing possible even at a globally negative (pressure) stress level, the temperature field and resulting deformations/ stresses inside the unrestrained sample are measured and evaluated.

3.2. Salt Rock Behavior under Cooling

First of all, the boundary conditions for the test equipment in the laboratory are being described.

While its deformation is completely free at all directions, the temperature impact is irregular. The copper element is cooled down from 313 K to app. 273 K causing the inner radius of the sample to reduce its temperature by ~20 Kelvin in less than 20 minutes. Meanwhile a radiation-fan-combination regulates the temperature of the surrounding air to stay constant at ~313 K. In various experiments temperature data is being collected for certain depths and heights inside the rock salt during a 1.5 h cooling phase using over 40 temperature sensors with platinum measuring resistors (PT100, see Figure 2).

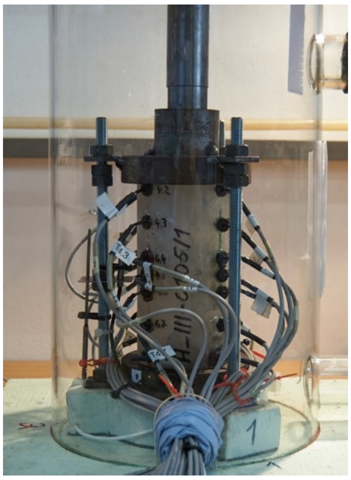

Figure 2. Experimental setup for recording temperature data

Considering the analytical solution for thermal stresses [6] it becomes clear that a temperature difference of 2 K in salt rock can cause stress differences of ~2 MPa. Therefore, it is expected to find cracks in the rock salt sample due to great temperature changes in short time. Figure 3 shows the results of temperature measurements inside the specimen (hollow cylinder with 180 mm height, 90 mm diameter and 30 mm borehole) during a 1.5 h lasting experiment at the location of the cold copper element, the cooling of the copper itself is shown in Figure 4.

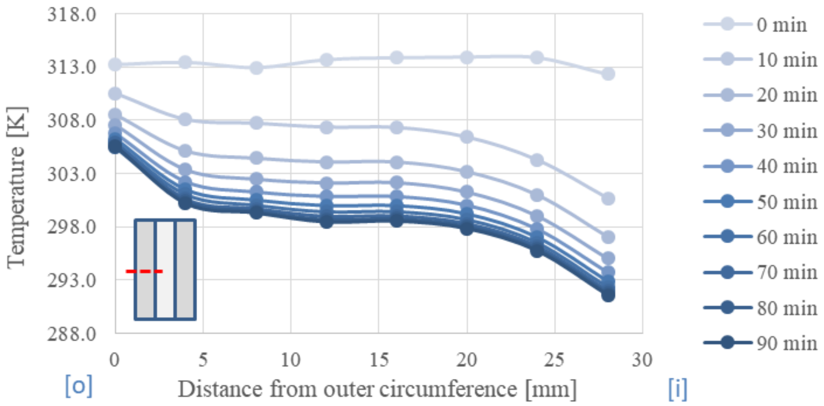

Figure 3. Temperature reduction of specimen during 1.5 h lasting experiment plotted every 10 min up to 90 min from outer (o) to inner (i)

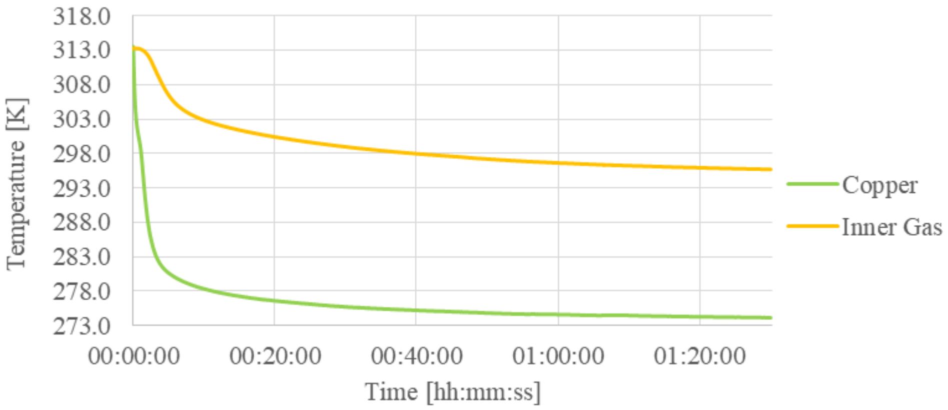

Figure 4. Temperature reduction of copper element and surrounding air during 1.5 h lasting experiment

Even though the copper reaches a temperature reduction up to ~40 K, the inner surface of the salt mass only cools down by ~20 K. The most likely reason is the convection-process between the copper and the salt. Furthermore, the radiation is not designed to keep the outer surface of the specimen at 313 K. Consequently, the body cools down through its whole diameter which causes deformations to spread and local stresses to be reduced.

Although the Acoustic-Emission sensor, connected to the specimen on the outside, showed definite activities at the beginning of the experiment, no visible cracks were found by macroscopic examination. While it cannot be excluded that micro-cracks occurred at the inside of the sample, another reason for the fracture-preventing stress reduction is the unrestricted deformation of the body in all directions. To optimize the testing scheme such mechanisms have to be explained, hence numerical calculations were simulated and analyzed.

4. Numerical Models

4.1. Temperature Induced Stresses in a Hollow Cylinder

Numerical models are used to find further information about the stress-strain relations resulting from temperature changes and respectively optimize the experimental setup. For this purpose the finite-differences-based software Flac3D (Itasca) [7] is used. As the experiments do not last longer than 2 h maximum, creep processes can be neglected from rock mechanical point of view. Therefore, it was considered sufficient to carry out elastic calculations based on Hooke’s law to get first insights.

In order to validate the numerical model, a mathematical analysis has to be done. The assumed elastic material properties for a representative rock salt are given in Table 1.

Table 1. Rock salt material properties.

Parameter	Value
Young’s Modulus E	20 000 MPa
Poisson’s ratio ν	0.25

W. Nowacki provides analytical solutions for the correlation between temperature and stresses in hollow cylinders [8] :

$$\sigma_r(r)=-\frac{3K\alpha_t}{(K-\frac{2}{3}G)+2G}*G*\Delta T*\left(\frac{ln(r_a/r)}{ln(r_a/r_i)}-\frac{(r_a/r)^2-1}{(r_a/r_i)^2-1}\right) \tag{2}$$

$$\sigma_t(r)=-\frac{3K\alpha_t}{(K-\frac{2}{3}G)+2G}*G*\Delta T*\left(\frac{ln(r_a/r)-1}{ln(r_a/r_i)}+\frac{(r_a/r)^2+1}{(r_a/r_i)^2-1}\right) \tag{3}$$

$$\sigma_a(r)=-\frac{3K\alpha_t}{(K-\frac{2}{3}G)+2G}*G*\Delta T*(\frac{2\,ln(r_a/r)-\frac{\lambda}{2\left((K-\frac{2}{3}G)+G\right)}}{ln(r_a/r_i)}+\left(\frac{(K-\frac{2}{3}G)}{2(K-\frac{2}{3}G)+G}\right)*\frac{2}{(r_a/r_i)^2-1}) \tag{4}$$

with

$$K=\frac{E}{3(1-2\upsilon)} \tag{5}$$

$$G=\frac{E}{2(1+\upsilon)} \tag{6}$$

$$\lambda=K-\frac{2}{3}G \tag{7}$$

where σ_r is the stress in radial direction, σ_t the tangential stress and σ_a the axial stress inside the cylinder. While α_t describes the thermal expansion coefficient and $r_{i/a}$ the inner/outer radius, r is for the radial distance from the cylinders center. These mathematical formulas are valid for the steady heating of the complete internal surface of a hollow cylinder and therefore must be compared to the actual setup with caution. The main results for a non-restraint, internally cooled sample can be reviewed in Figure 5:

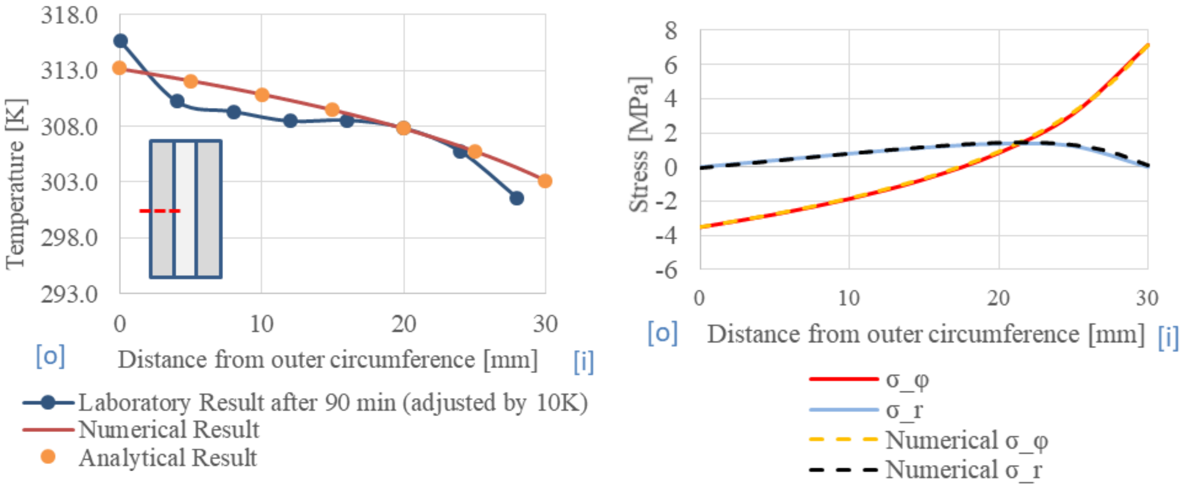

Figure 5. Results of temperature distribution (left) and stress distribution (right) for a hollow cylinder internally cooled by 10 K (along the profile shown)

The diagrams illustrate the results throughout the cylindrical specimen in horizontal direction from outer circumference (≙ 0 mm) to inner boundary (≙ 30 mm). For analytical calculations the inner surface was cooled down over its complete height of 180 mm by 10 K. This assumption results from laboratory investigations showing that the temperature difference between inner and outer surface of the cylinder are about 10 K maximum. Instead of reducing the outer surface by 10 K and the inner by 20 K, the total inner cooling is set to 10 K, satisfying the elastic calculation. The measured values for the individual measuring points after 90 minutes in the rock salt specimen from Figure 3 are adjusted by 10 K in Figure 5 to match the numerical model and substantiate the assumptions made in the models. In this case, numerically calculated temperatures and stresses match the mathematical results in a good manner: Circumferential stresses are higher at the cooled side, causing strong tension, and radial stresses increase moderately at the inside of the specimen.

While the elastic numerical model subsequently shows the same results as the analytical solution, a more complex one differs. The local reduction of the cooling area inside the borehole is material to this. Convection processes are still incorporated when developing a more detailed numerical model and according to this, all remaining surfaces are now cooled down by 10 K while the inner temperature is locally reduced by 20 K. Figure 6 shows high circumferential stresses at the inside of the specimen, as well as increased tension in the vertical direction.

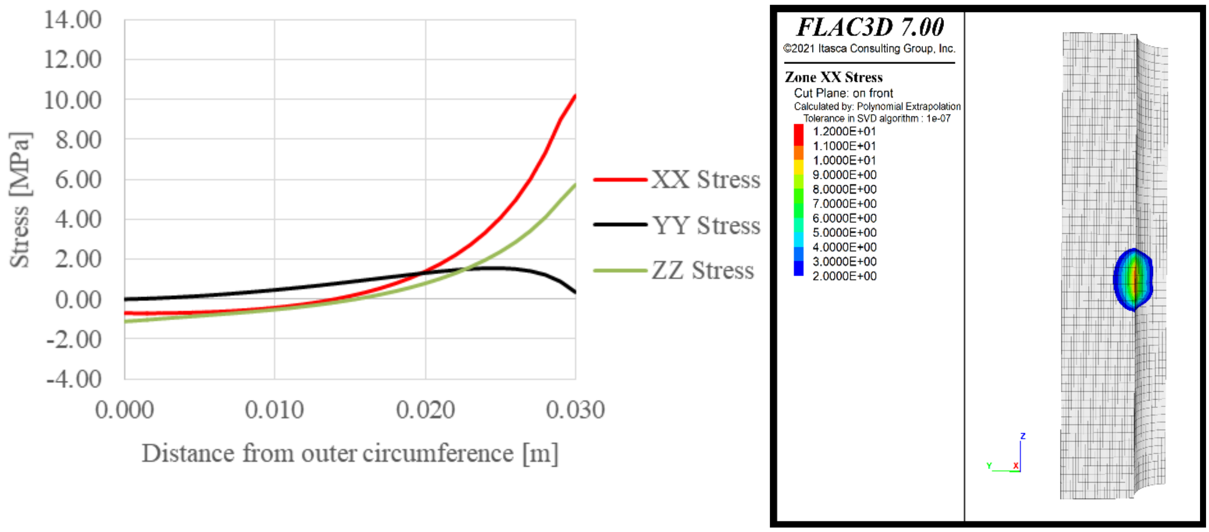

Figure 6. Stresses resulting from a locally limited cooling inside the cylinder with a temperature reduction of the remaining surfaces by 10 K (No mechanical loads applied)

Under these circumstances and regarding the tensile strength of rock salt to be of ~2 MPa, fractures could occur inside the specimen, the results of several acoustic-emission tests support the thesis.

However, the area where fracture could be found is located at the inside of the borehole and is difficult to access (Figure 6). Cracks are probably only a few millimeters deep. To make them visible a fluorescent liquid is being used to get a better impression of the fracturing process within the specimen.

Within the ongoing research project “LARISSA” it has to be investigated, whether a more complex and detailed consideration of the assumed constitutive law, the convection process and a consolidation of the specimen have an influence on the fracturing behavior.

In order to get first results evoking gas-driven fractures at a global pressure-level, the testing technique is changed. While the testing facility is optimized to enable a greater stress reduction through cooling, stresses resulting from a temperature decrease are reproduced mechanically.

5. Mechanical Testing Strategy

The mechanical reproduction of the temperature decrease in rock salt storage caverns is realized in the triaxial testing cell at rock salt specimens under axial and circumferential loading and inner gas pressure (nitrogen). As the temperature in the cavern cools down, the vertical and circumferential rock stresses are expected to decrease [5]. This is illustrated in the triaxial cell by the pressure-controlled reduction of one of these pressure components at constant internal pressure and constant axial respectively circumferential pressure. Due to the one-sided pressure reduction, a crack orthogonal to the unloading direction is expected in the rock salt test specimen. In the “La-thi-ga” research project [1], a stress difference between internal gas pressure and axial pressure of 2 to 4 MPa was determined for the horizontal fracturing with the same test setup. Based on an average tensile strength of rock salt of about 2 MPa and a conservatively assumed Biot coefficient of 1, pressures in this range, which lead to fracture of the specimen, are also to be expected in the case of circumferential pressure reduction. In the following, the test results and evaluation are presented for one experiment of each of the different unloading directions.

The same experimental apparatus as in Figure 1 is used, but without the cooling-shaft. The specimens have an outer diameter of 90 mm and a height of 180 mm; the inner diameter was 30 mm for the unloading test in axial direction and 12 mm for the unloading test in radial direction. All tests are carried out at approx. 293.15 K (room temperature) and a relative humidity of approx. 50 %, while the starting pressure level is set to the same value for axial and circumferential loading. To prevent prior percolation, the internal gas pressure is kept 1 MPa below the mechanical loading level - considering the mathematical definition for pressure to be positive here. In both tests, the initial pressure for the axial and circumferential pressures before unloading is 10 MPa, which is approached with 1 MPa/min. The initial pressure of the internal gas pressure is 9 MPa and is increased with an offset of 0.5 MPa at the same pressure rate.

Unloading of the axial pressure respectively circumferential pressure at a constant pressure level for the other controllable pressures also is performed with a rate of 1 MPa/min. The axial unloading is terminated as soon as the axial piston has shifted by 3 mm. The circumferential unloading is stopped if the pressure piston for the oil volume of the cell is decreased by 20 mm.

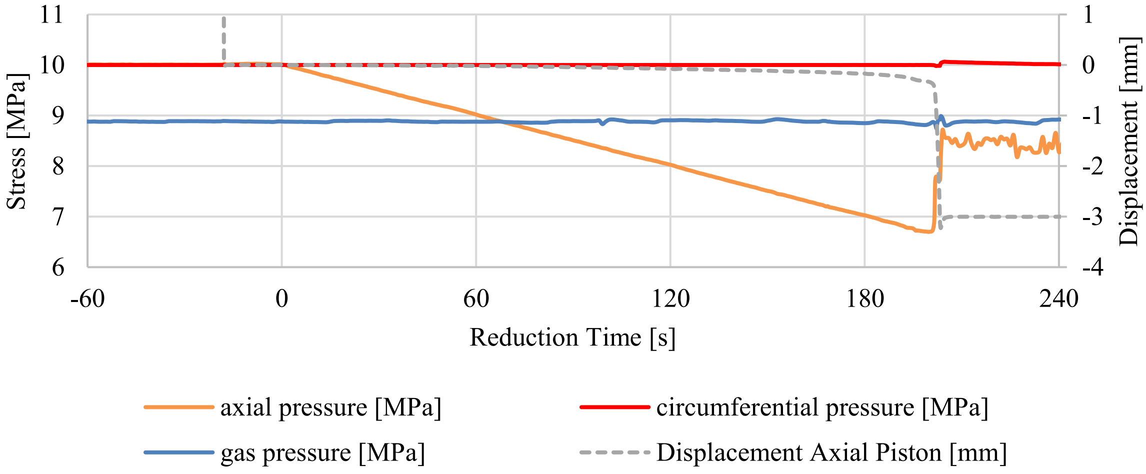

Figure 7. Unloading in axial direction at starting pressures of σ_{ax} / σ_{conf} / p_i = 10/10/9 MPa

First, the experimental results with reduction of axial pressure will be presented. The displacement of the axial piston in the first experiment increases rapidly at a reduction time of 200 seconds and the axial unloading is stopped after reaching a displacement of -3 mm. A stress difference of max. 2.14 MPa between the internal gas pressure and the axial pressure is reached (see Figure 7). After the removal of the specimen from the triaxial cell, a horizontal fracture could be seen at mid specimen height along the grain boundaries and through individual grains (see Figure 8).

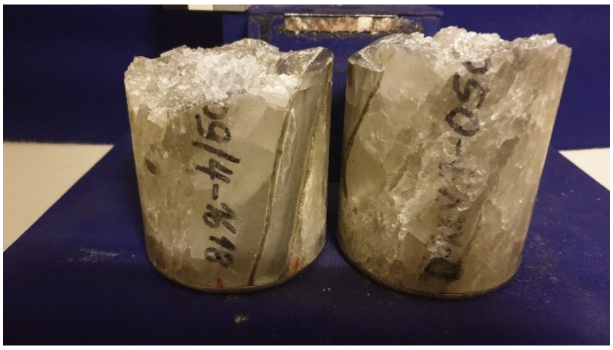

Figure 8. Front view of the cracked specimen after axial pressure reduction

In the next step, the circumferential pressure was reduced at another specimen. Furthermore, the borehole diameter for this test was 12 mm Intention of the borehole reduction was to minimize the possible influences on the surrounding specimen caused by the borehole drilling. The actual influence cannot yet be estimated. The starting pressures before unloading are again 10 MPa for axial and shell pressure and 9 MPa for gas pressure, the reduction rate is 1 MPa/min.

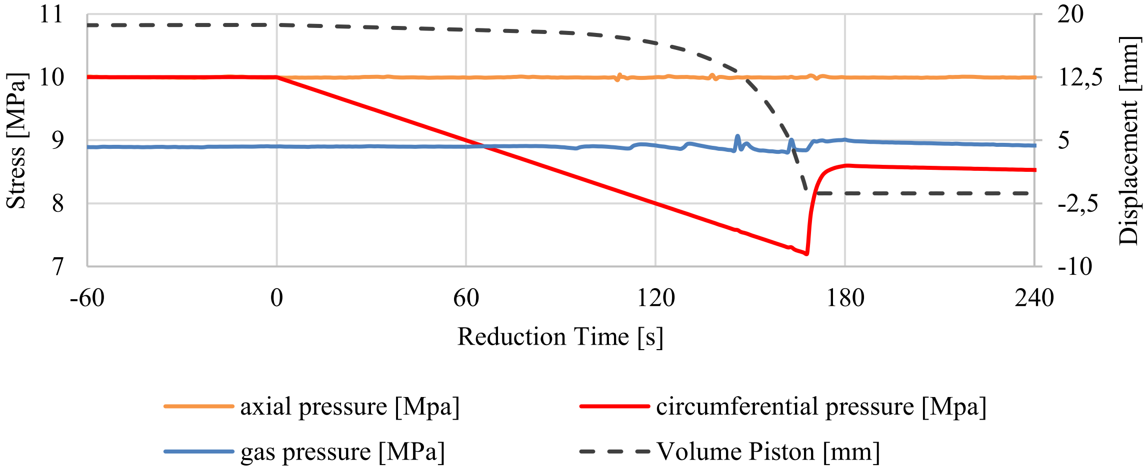

Figure 9. Unloading in circumferential direction at starting pressures of σ_{ax} / σ_{conf} / p_i = 10/10/9 MPa

The experiment is stopped after approx. 170 seconds and a stress difference between gas and circumferential pressure of 1.70 MPa, as the piston of the oil volume has shifted by 20 mm (see Figure 9). After sample removal, no cracks are directly visible on the rock salt. However, percolation with fluorescent medium and observation under UV light shows vertical cracks through the specimen (see Figure 10).

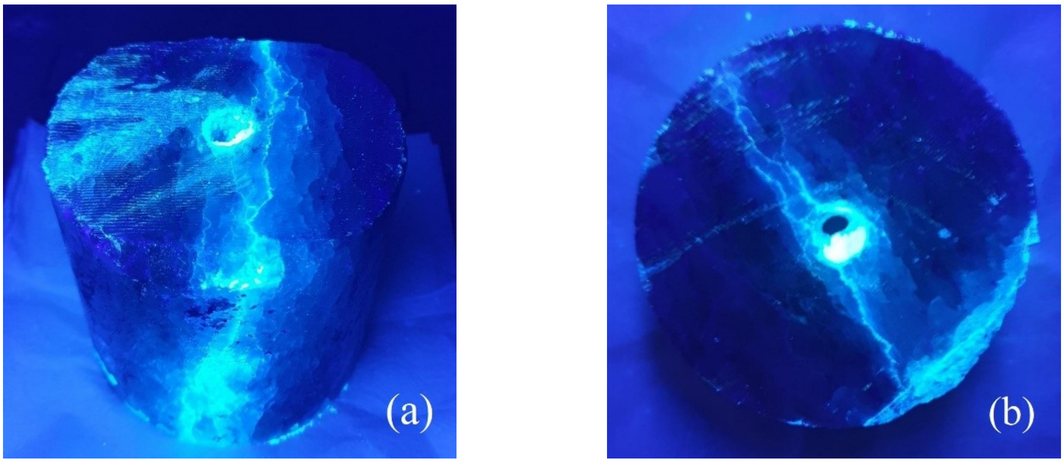

Figure 10. Separated rock salt sample, flowed through with fluorescent medium under UV light (a) Middle horizontal cut (b) middle horizontal section of the upper half of the sample

The fracture propagates vertically in radial direction, lying on an axis, and goes through the entire diameter of the test specimen.

In summary, it could be shown that a reduction of the axial or circumferential pressure below the applied constant gas pressure leads to a fracture of the specimen. The reduction of the axial pressure was interrupted at a stress difference of 2.14 MPa, the reduction of the circumferential pressure at a stress difference of 1.70 MPa. The next step is to examine at which stress difference the fracture propagation starts, how this can be quantified and which influences result from the rock salt properties, possible stratifications and grain sizes.

6. Conclusions

During the first laboratory tests using the novel testing facility at the Institute for Geotechnical Engineering in Hannover some conclusions could be drawn regarding the generation of fractures by a local temperature reduction in cylindrical rock salt specimens without further external loads. Numerical analyses indicate regions of high tensile stresses in the hollow body and confirm the possibility of fracturing due to a local temperature reduction by 20 K close to the borehole. An investigation of acoustic emissions produced during a 1.5 h testing phase reveal the frequent appearance of events in the first minutes of the cooling-phase. Even though macro-cracks haven't been visible after a laboratory test, damage could occur at the inner space of the sample. Further methods of evaluation are currently being discussed and might extent these findings.

In general, the incidence of fractures at caverns walls resulting from significant temperature changes during gas-removal is unavoidable. To better estimate their behavior, further investigations combining the cooling process with mechanical loads in the triaxial cell are necessary. As the fluid-pressure plays an important role for the propagation of cracks at global pressure-levels, first results could be achieved by replacing the cooling-process mechanically reducing the internal stresses of the specimen. Horizontal and vertical fractures could be generated orthogonally to the smallest principal stress, which was below the applied internal gas pressure, and could be detected visually. The possibility of fracture existence caused by temperature induced stress differences and gas pressure inside the cavern surrounding rock salt is thereby proven. Further mechanical experiments without active thermal cooling could focus on crack initiation and propagation. Laboratory results then need to be combined with detailed investigations of the temperature fields surrounding salt caverns and their fracture behavior for different cavern dimensions in order to contribute to the safety and benefit of the underground storage system.

Acknowledgement

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