RESULTS OF THE THERMOMECHANICAL EXPERIMENTS PERFORMED IN THE 300M HOLE IN THE ASSE SALT MINE (FRG)

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ABSTRACT

In 1979 a 300 m deep borehole was made in the ASSE salt mine in Remlingen (FRG). The hole was drilled from the 750 m floor using a dry-drilling technique. Directly after the drilling operation in December 1979 a series of thermo-mechancial experiments started. Convergence is measured under isothermal and nonisothermal conditions. The thermally induced pressure of the salt on a cylinder, simulating a canister, was measured for several thermal loads. An evaluation of the most important results is given. The role of the lithostatic pressure (p) on the results is discussed.

INTRODUCTION

In the Netherlands research has been performed on the design of a high-level radioactive waste repository in a salt formation. The safe disposal depends on the performance of the overall waste disposal system, and must be analysed by means of safety studies. In order to be able to describe and quantify this performance the time-dependent thermo-mechanical behavior of rock salt must be known. This behavior can be determined by means of laboratory experiments or with in-situ tests. Both types of experiments are necessary and in fact complementary. Laboratory tests are suitable to determine the influence of separate parameters under well defined circumstances while in-situ experiments are needed to simulate realistic and repository relevant conditions. In-situ tests can be used also in the validation process of the numerical tools which are needed to analyse the short and long term behavior of the repository. In-situ tests however can also be useful in the derivation of the constitutive behavior of rock salt. In this paper a summary is given of the most important results of the experiments being performed in a borehole in the ASSE II salt mine. Detailed information is given in Ref. 1.

EXPERIMENTAL RESULTS

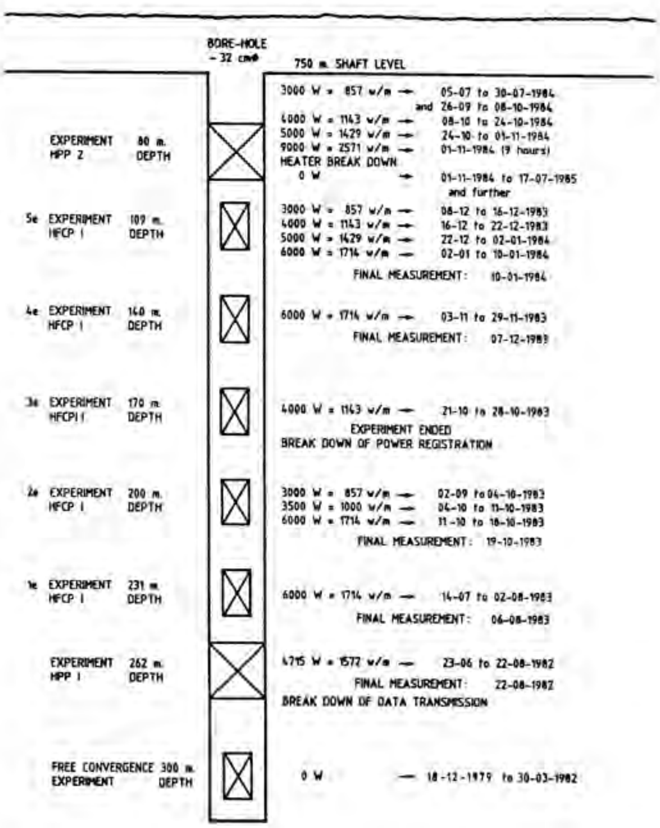
The experiments described in this paper are performed in a 300 m deep dry-drilled borehole with a diameter of 315 mm. The borehole was drilled from the 750 m level and finished in December 1979 (2). An overview of all experiments performed is given in Table I. The tests will be described now in the historic order.

Isothermal Free Convergence

At the bottom of the hole the free convergence of the walls of the hole was measured with six dials mounted at a circular plate at several locations in circumferential direction. The dials were read by a television camera which sent the picture to a monitor station at the 750 m level. The complete result is given in Fig. 1, while all numerical values are reported in Ref. 2. It can be seen that at this depth of 1042 in the ASSE the convergence is rather slowly. In one year the diameter of the hole was reduced with 1 cm. This implies that in a repository under the same circumstances with respect to pressure, temperature and brine concentration, there can be a considerable time period between the drilling of the hole and the emplacement of containers with the waste. Or in other words it is not necessary to drill the holes with much oversize. These convergence results are used also to derive a constitutive relation. The procedure used is described in detail in Ref. 3 where it is shown that the measured convergence data of the first 200 days corresponds to a secondary

TABLE I

Overview of Experiments



creep law with a stress exponent n = 5.5 Further analysis showed that assuming E = 7600 MPa, υ = .3, $\alpha = 4\ 10^{-5}$ and p = 22 MPa the constant in the creep law $A = 8.8\ 10^{-11}\ MPa^{-n}\ days^{-1}$. After this evaluation of the first 200 days the convergence was calculated for the following time period until 800 days. A comparison of this calculation and the measured convergence show a good correspondence.

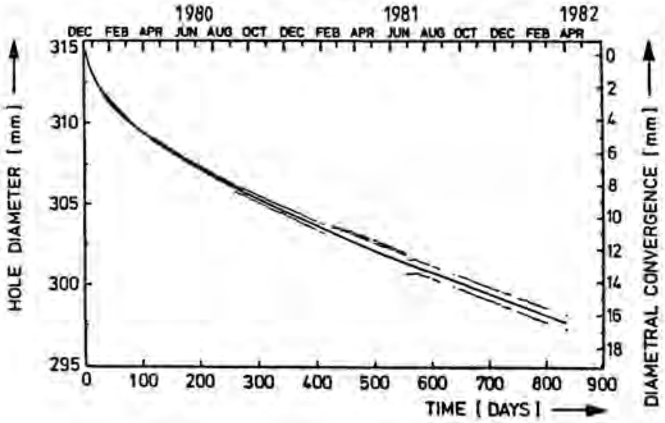


Fig. 1. Covergence of ECN Hole at 292 m below 750 m Floor.

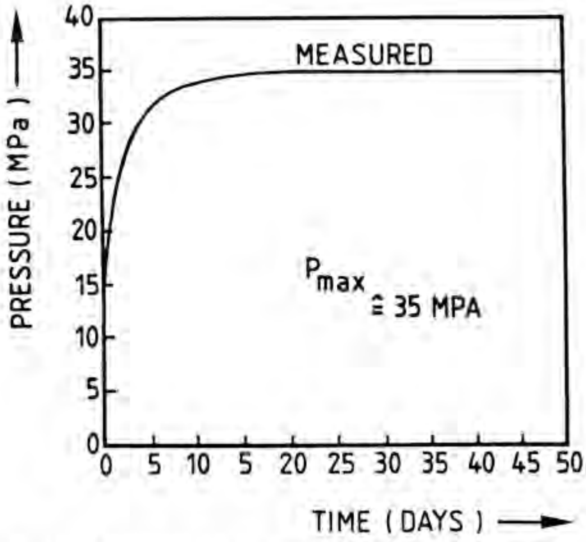


Fig. 2. Pressure at a Depth of 262 m Below 750 m Floor (t_{max} = 177^{0}C).

First Heated Pressure Test

At a depth of 262 m in the borehole an experiment is performed with an inductively heated cylinder which can be observed to simulate the thermo-mechanical loading conditions caused by a container filled with heat-generating nuclear waste. The heated length was 3 m and the total input was 5000 W which results in a salt termperature with a maximum of 177^{0}C during the test period. The aim of this test was to measure the pressure on the heated cylinder. This pressure is caused by the thermal expansion of the locally heated salt and the accelerated creep of the rock salt. The pressure could be derived from the measured deformation of the heated cylinder (1). This cylinder was designed such that this deformation was elastically. The resulting pressure history on the midplane of the heated cylinder is given in Fig. 2. It is analysed that the error in the absolute magnitude of the pressure could be maximal 15%. The time history is considered to be more accurate. It can be seen that the pressure is built up in a relatively short-time period (less than 1 month). When this maximum is reached the pressure decreases slowly. The maximum value is about 35 MPa (345 bar). As the loading conditions are relevant for a repository it could be anticipated that the waste containers will be loaded by an external pressure of about 35 MPa. The influence of the lithostatic pressure is discussed below. Further analyses have shown that the resulting pressure is almost insensitive for the temperature dependency in the creep law. This implied that this pressure test could not be used to derive the temperature dependency of the creep law.

Heated-Free Convergence

At five different depths in the borehole, measurements are performed with a heated cylinder and a extreme large gap (5 cm in radial direction) between the heater and the salt. Due to this large gap the covergence of the heated salt could be studied. The displacement of the salt could be measured with a system of 30 swingarms with transducers divided over the 3 m length and the circumference of the cylinder. More details on the design and the result of the first test is given in Fig. 3. This test ran for only 22 days because in that period the initial gap of 5 cm was closed with salt due to the accelerated convergence. As the heat input was realistic for a repository this result implies that the period between filling the borehole with waste and creep induced closure of the hole over the whole heated length is extremely short. This period is much less than 1 month because of the fact that the initial gap will be less than 5 cm. Numerical analyses showed that the convergence of the locally heated salt was very sensitive for the activation energy Q in the Arrhenius type of a temperature dependent creep law. The convergence could be fit with Q/R = 8250 K (Q = 68.6 KJ/mol).

Second Heated Pressure Test

This experiment at a depth of only 80 m in the borehole was primarily performed to test the influence of the temperature on the pressure build-up. Therefore, the heat input was planned to be step-wise. However, due to an unforeseen problem with the power supply and an unwanted short circuit in the heater this plan could not be performed completely. These problems did not result in a useless experiment but made it extremely useful. In Table I the final history of heat input is given. Figure 4 shows the resulting pressure on the heated cylinder. This pressure was derived in essentially the same way as for the first pressure test. The most interesting part of the experiment is caused by the two periods with zero heat input. In these periods the pressure decreases and the question appeared how this pressure was related to the rock pressure at that location. It was felt that the rock pressure should be lower than the decreasing pressure or at least could not be much higher. This should imply that at this location the lithostatic pressure was not higher than 100 bars (1). This was rather surprising as the pressure due to the static weight of the sediments was 178 bar. An explanation of the reduction could be found in the stress redistribution caused by the large evacuated rooms in the ASSE.

INFLUENCE OF THE LITHOSTATIC PRESSURE

Analyses showed that the lithostatic pressure has a considerable influence on the quantities measured in the borehole. The measurements showed that the lithostatic pressure was much lower than assumed a priori which means that consitutive results derived of the experiments under the assumption of a high pressure, must be reconsidered. The measured results however might also be used directly for safety evaluations. In the presentation of the results these direct implications were indicated. For the use within this respect for other salt formations with the same thermomechanical properties the influence of the generally higher lithostatic pressure has to be evaluated. This evaluation will be given here. An analytical treatment (4) of the creep behavior of thick-walled circular cylinders with internal pressure p showed a dimensionless time τ which made the governing differential equation a function of only one material

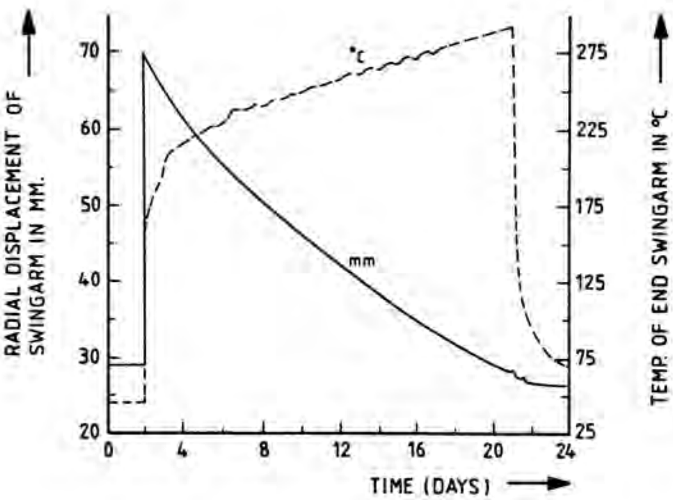


Fig. 3. Temperature and Convergence During the First Heated Free Convergence Test.

parameter viz. the Norton exponent of the stress n. This implies that the isothermal free convergence of a circular borehole with radius a can be written as (6):

$$u(t) = u^{el} f(\tau, n) \qquad (1)$$

where:

$u^{el} = \frac{3pa}{2E}$ (Elastic radial deformation)

$d\tau = (p\sqrt{3})^{n-1}$ EA dt = (normalized time)

f = normalized convergence

Finite element analyses have shown that the influence of p, E, A and α on the convergence can indeed be taken into account with this relation, see Fig. 5.

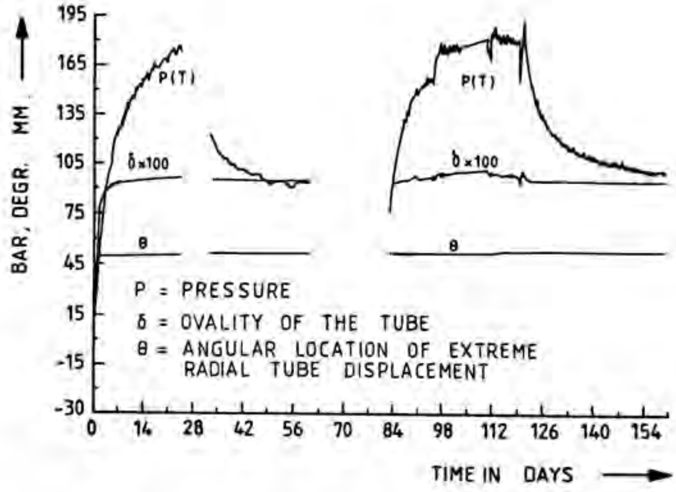


Fig. 4. Measured Pressure History on the Midplane of the Second Heated Pressure Tests.

This knowledge can be used to derive the covergence u_a for an arbitrary pressure p_a from the measured convergence u_m for a pressure p_m as far as the same salt is concerned.

The transformation is given by:

$$u_a(t) = u_m\left(\left(\frac{p_a}{p_m}\right)^{n-1} . t\right) \; . \; \frac{u_a^{el}}{u_m^{el}} \qquad (2)$$

This procedure can be used also to evaluate the effect that A and n were derived using p = 22 MPa while the last experiment gave indications that p was much lower. In Ref. 1 the lithostatic pressure at the bottom of the borehole was estimated to be 17 MPa. This means that n remains unchanged and A should be 4.8 10^{-10}. These analyses also showed that the covergence rate is a monotonically decreasing function of time. The analyses further showed that the ultimate stationary convergence rate can not be reached in an experiment in a large salt formation.

The influence of the lithostatic on the pressure which builds up around a container with heat-generating waste could not be evaluated with the

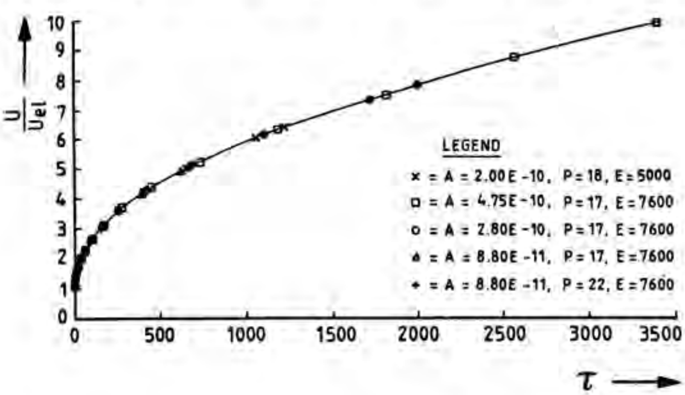


Fig. 5. Normalized Convergence as Function of Normalized Time τ.

parameter τ because of the presence of a thermal strain field. It nevertheless could be evaluated by means of parametric finite element analyses. In Fig. 6 a typical result of such an analysis is shown. Here the time history of the radial stress on the container is given for several values of the lithostatic pressure. It can be observed that for times larger than 10 days the radial stress is the sum of the lithostatic pressure and a thermal stress which is independent of the lithostatic pressure.

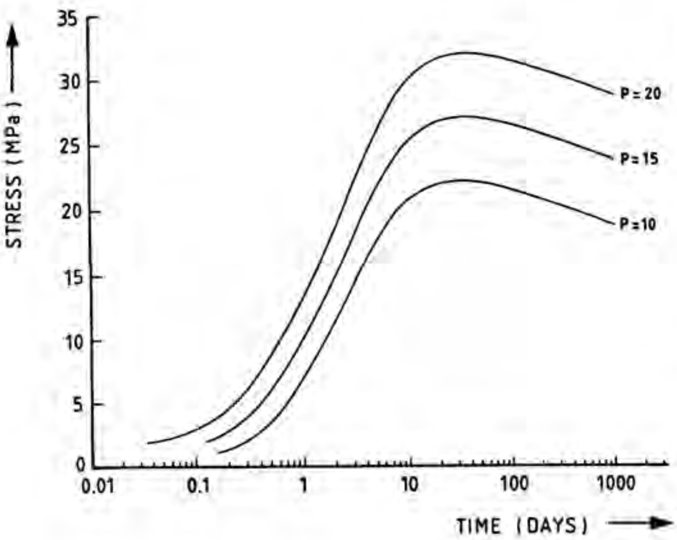


Fig. 6. Role of p On Temperature Induced Stresses.

The radial stress $\sigma_{r,a}$ for an arbitrary lithostatic pressure p_a can therefore be derived from the measured stress $\sigma_{r,m}$ for a lithostatic pressure p_m according to:

$$\sigma_{r,a}(t) = \sigma_{r,m}(t) + p_a - p_m \tag{3}$$

Realizing that the first pressure test gave a maximum of 35 MPa while the lithostatic pressure was 17 MPa means that for a lithostatic pressure of 22 MPa the maximum radial stress should be 40 MPa. This value which also found in numerical analyses (5) thus, should be used as indication for the maximum compressive stress on waste containers at a depth of 1000 m and a heat of 177^{0}C. The influence of the lithostatic pressure on the heated-free convergence could not be described with a simple transformation. A higher pressure gives a higher convergence and closes the gap between container and borehole wall faster as can be deduced from Fig. 7 where some finite element results are presented.

Measurement of the Lithostatic Pressure

The character of all measurements of the lithostatic pressure is such that in fact the state of stresses which ought to be measured is distorted by the measuring system. Some remarks will be given here to a measurement in a borehole which is drilled from a gallery. Results of numerical analyses (1) have shown creep-induced redistribution of the stresses around a gallery and the stresses around the borehole.

The gallery in the neighborhood of the measuring location initiates the stress redistribution to

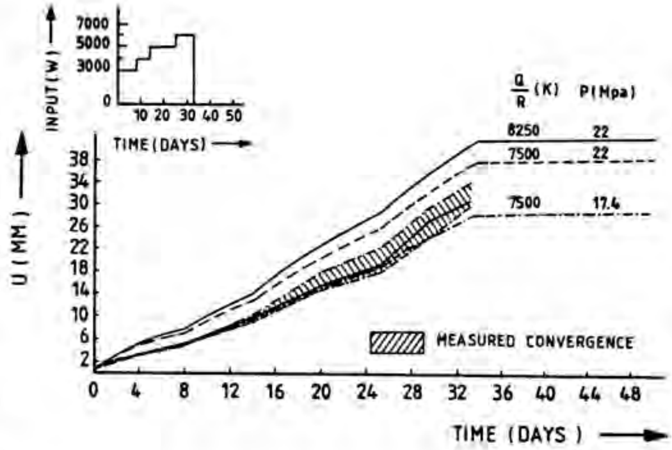


Fig. 7. Comparison of Measured and Calculated Convergence of the Fifth Heated Free Convergence Test.

stresses of about 40% lower than the lithostatic pressure. Due to the bore hole in which the measurement is performed it takes an extremely long time to reach this redistributed stress. It can be deduced from the second pressure test where the power was shut off that a non-isothermal pressure measurement gives a considerable improvement. Numerical analyses are always necessary to derive the lithostatic pressure from the measured pressure history.

CONCLUSION

In this paper the results are presented of a series of experiments performed in the ASSE mine in a 300 m deep dry-drilled borehole. It has been shown that these results can be used to derive the time and temperature dependent constitutive behavior of rock salt with a given elastic behavior. As the experiments are performed under thermal conditions relevant for the present design of a repository the direct relevance of the experimental results for the safety evaluation is discussed also. It could be concluded that an initial radial gap of 5 cm between container and borehole was closed due to the thermo-mechanical behavior of the salt within 20 days. After that period a compression on the container builds up. The measured maximum compression was 35 MPa. It is shown that for a repository at a depth of 1000 m and a lithostatic pressure of 22 MPa the maximum compression will be 40 MPa. A discussion is given of the influence of the lithostatic pressure on the isothermal borehole convergence and on the non-isothermal stress distribution. It is shown that both influences could be given with a simple transformation.

ACKNOWLEDGMENT

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