Creep Rupture Criteria for Rock Salt

R. B. Rokahr and K. Staudtmeister
Institut für Unterirdisches Bauen
Universität Hannover
Hannover, Federal Republic of Germany

ABSTRACT

Whereas comprehensive research projects have been carried out and published on the determination of the deformation behaviour of rock salt under long-term load conditions, few laboratory or theoretical investigations have considered the problem of creep rupture behaviour. The present report discusses the results of creep tests on rock salt under triaxial indirect tensile stress, under test conditions that included tertiary creep and led to creep failure. The results clearly show that the achieved failure strains are dependent on the strain rate, and that the latter is mainly dependent on the deviatoric and isotropic stress levels and on temperature. Failure strains above 25% were reached. Finally, the results were evaluated with respect to the formulation of creep rupture criteria with which the dimensioning of rock salt caverns can be made, under consideration of the long-term load-bearing behaviour.

INTRODUCTION

Within the framework of a rock-mechanical stability analysis of rock salt caverns, investigation of the long-term load-bearing behaviour of the cavern is of particular significance, because rock salt possesses a material behaviour that is strongly time-dependent. Thus, over the required operating periods of several decades, under certain circumstances significant cavity convergence and stress transfer to the surrounding rock mass can be expected, and this may lead to an impairment of the stability of either new or already constructed cavern installations. For this reason, considerable efforts have been undertaken in recent years, on the one hand to obtain an insight into the viscous material behaviour of rock salt under mechanical and thermal loads, and on the other hand to be able to quantitatively determine the long-term load-bearing behaviour of caverns. Numerous publications have been issued on the subject, and thus further discussion of general aspects is unnecessary.

The concept of a differentiated idealization of the material behaviour of rock salt is contained in a dimensioning concept that has been developed by the Institut für Unterirdisches Bauen, Hannover, West Germany. The concept has been broadened by a consideration of limiting conditions in the load-bearing behaviour of caverns. From the engineering point of view, the limiting conditions can then be used to prove cavern stability via consideration of possible failure modes. In the case of rock salt caverns, as a result of unusual aspects in the construction and utilization on the one hand, and due to the rock-mechanical properties of rock salt on the other hand, two limiting conditions are considered to be definitive with respect to the proof of stability:

- Limiting condition 1: Proof of short-term stability
- Limiting condition 2: Proof of long-term stability.

Limiting condition 1, with the proof of short-term stability, is based on the fact that in comparison to the total lifetime of the cavern of a number of decades, the duration of the construction and the commissioning phases—between a few months and approximately two years, according to cavern volume—is relatively short. Cavern design is closely related to this limiting condition, with the aim of developing an optimum cavern design under consideration of leaching requirements in respect of the in situ geological and rock-mechanical conditions. Because the rock mass surrounding the cavern must be able to accommodate the additional loads without failure and with a sufficiently large safety margin, it is assumed that the material behaviour of rock salt can be described by an elastic, non-linear plastic material law.

In the case of limiting condition 2, relating to the proof of long-term stability, it is assumed that the rock mass can safely accommodate stresses resulting from the utilization and operation of the cavern in the long term too, i.e., over a period of a number of decades. One of the major factors is the convergence to be expected, which is mainly dependent on the viscous material behaviour and must not exceed certain limiting values with respect to creep failure and surface subsidence. It is assumed that the material behaviour of rock salt can be described by a viscous material law. The necessary extrapolation requires particular care.

Five criteria for the evaluation and judgment of the theoretical results that form the basis for the design of cavern installations have been proposed (Lux and Rokahr, 1980). The following discussion relates to point 4 of their criteria, relating to restriction of the convergence, and should be considered to be a proposal for the formulation of a criterion for the judgment of creep rupture. At this stage, it should be made quite clear that the creep rupture tests carried out up to now by the Institut für Unterirdisches Bauen are not comprehensive enough to enable a proposal to be made of a comprehensive and complete criterion for the judgment of creep rupture in rock salt. However, the initial results of the investigations are promising, and it is planned to continue this line of investigation in the future.

PREVIOUS INVESTIGATIONS ON THE PHENOMENON OF CREEP RUPTURE

Experience shows that in the case of rock salt, as with many other materials, it is necessary to differentiate between strength with respect to short-term stresses and an often very much lower strength in the case of long-term stresses. The difference between the short-term strength and the long-term strength becomes increasingly marked with an increase in the significance of the viscous material behaviour. For this reason, when using such materials for technical purposes, when dimensioning, it is necessary to include a factor to take account of the duration of the stress. Whereas comprehensive information is available on investigations on the deformation behaviour of rock salt under long-term loads, up to now few laboratory or theoretical investigations have been concerned with the problem of creep rupture behaviour.

In several publications, so-called creep rupture criteria have been proposed for the definition of the long-term strength of, above all, metallic samples. However, the proposals are based on considerably differing assumptions. Judgment of the long-term strength has been based on:

a) the time t_B to creep rupture (life fraction rule)
b) the stress σ_B which can be accommodated in the long run
c) the rupture strain (strain fraction rule)
d) the strain energy with respect to time.

Theoretical investigations on the stress and displacement fields in the vicinity of cavities in rock salt deposits show that the assumption of a non-linear stress/strain relationship indicates a reduction of the deviatoric stress component with a simultaneous increase of the non-linear strain component. Thus initially, it appears meaningful to derive limits to the material loading from the strain or the strain energy.

Knoll (1973) has carried out comprehensive laboratory and theoretical investigations on carnallitite and rock salt with respect to the safe and economical dimensioning of pillars in rock salt mines. While considering the load duration, pile dimensioning should be based on uniaxial long-term creep tests, which yield information on the deformation behaviour and the creep rupture behaviour in relationship to the stress condition and the shape of the test sample. The tests clearly show that whereas under high stress levels a brittle failure of the material can be expected, at medium and low stress levels a ductile creep failure is more likely.

With respect to the judgment of the lifetime of rock salt and carnallitite pillars of differing dimensions, Knoll (1973) quotes the creep rupture time and the creep rupture strain in relationship to the stress level and the ratio of pillar height to pillar diameter (h/d). According to his investigations, load ranges can be determined for each salt type and ratio of h/d which either permit indefinite failure-free pillar life, or limited lifetime and slow or suddenly occurring creep rupture. For example, for a ratio $h/d = 2$, test samples were able to withstand a stress of up to 25% of the uniaxial compressive strength σ_u indefinitely, whereas at stress levels of approximately 75% or above, sudden failure occurred after a relatively short time. However, the dimensioning criteria quoted by Knoll (1973) cannot be transferred to the dimensioning of salt caverns, since the loading conditions in mining (mainly uniaxial pillar loads) differ fundamentally from those encountered in cavern construction (three-dimensional stress conditions).

Multi-axial creep rupture tests were first evaluated by Nair and Singh (1973). It is assumed that the maximum main stress difference is the controlling stress and that the onset of creep rupture is mainly related to the occurrence of tensile strain. It should be noted that such strain conditions are not necessarily related to tensile stress, but in accordance with the in-situ conditions can also occur under triaxial compressive loads.

Rupture creep tests (Figure 1) clearly show the linear relationship between the stress difference $|\sigma_1 - \sigma_3|$ and the time to failure t_B. The figure covers a time to failure of approximately 7 h to over 1000 h, i.e., the curve can also be used for very short tests, where most likely no tertiary creep takes place. The effective stress lies between 36.5 MPa and 66.9 MPa. Nair and Singh (1973) consider the effects of the average stress to be insignificant. In contrast to this, our own test results (curve with triangles in Figure 1) indicated a different time to creep

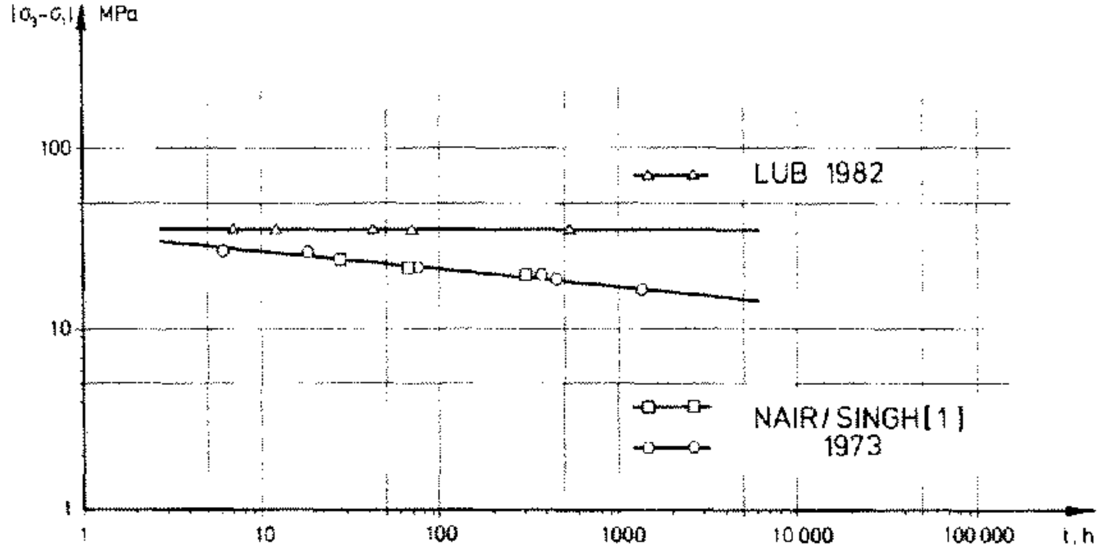

Figure 1. Results of Creep Rupture Tests plotted in a double logarithmic form carried out by Nair and Singh (1982) and LUB.

rupture for the same main stress difference but with differing isotropic stress components. This phenomenon is particularly significant in the case of rock-mechanical considerations, because in the vicinity of the cavity, three-dimensional stress conditions can occur with differing isotropic and deviatoric components, and thus if the effects of the isotropic stress component on the creep behaviour are ignored, this can lead to underestimation of the time to failure.

Within the framework of comprehensive theoretical and experimental investigations, Menzel and Schreiner (1977) have formulated a creep rupture criterion that is based on considerations of the energy involved. It is principally based on the assumption that the total energy input required in a short-term test up to the point in time when the sample fails is the same as the plastic deformation energy required in a creep test up to the time point of the start of creep failure. The stress/strain relationship for the two cases and the estimated plastic deformation energy with respect to unit volume are shown schematically in Figure 2.

Whereas in short-term tests with constant load increase, the stress σ_{eff} increases constantly until the failure point has been reached, in creep tests a particular constant effective stress is applied for the entire test duration.

To determine the time to failure t_B to be expected, on

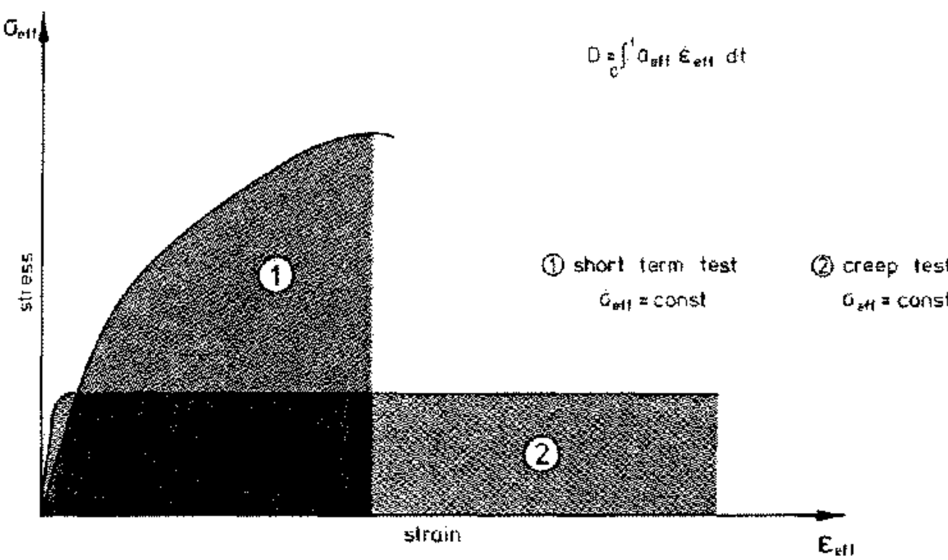

Figure 2. Determination of the Plastic Deformation Energy

the one hand it is necessary to determine the plastic deformation energy from short-term tests, and on the other hand the change in effective strain with time must be known, i.e., a suitable material law must be available. The determination of the time to failure t_B will be exemplified in the following for the case of creep tests carried out by the Institut für Unterirdisches Bauen on rock salt samples from the North German ASSE deposit. It proved possible to satisfactorily describe the results of the triaxial indirect tensile stress tests with a stress difference $|\sigma_1 - \sigma_3| = 20$ MPa and a test duration of 16 days both with the material law according to the MENZEL/SCHREINER equation and the material law, LUBBY 2, which was developed by the Institut für Unterirdisches Bauen (below).

The viscous strain and strain rates measured during the test and the corresponding results obtained from the two material laws are shown in Figure 3. The parameters were determined by curve-fitting. For the case of triaxial extension under constant load:

MENZEL/SCHREINER

$$\dot{\varepsilon}^v = A \cdot \sigma_{eff}^{\beta} \cdot (\varepsilon_{eff}^v)^{-\mu}$$

with:

$A = 3{,}5 \cdot 10^{-23}$ MPa$^{-9{,}7}$
$\beta = 9{,}7$
$\mu = 2{,}8$

respectively,

$$\dot{\varepsilon}^v = K \cdot m \cdot \sigma_{eff}^{n} \cdot t^{m-1}$$

with:

$K = 2{,}31 \cdot 10^{-6}$ MPa$^{-2{,}5}$ d$^{-0{,}258}$
$n = 2{,}5$
$m = 0{,}258$

LUBBY 2

$$\dot{\varepsilon}^v = \left[\frac{1}{\bar{\eta}_M} + \frac{1}{\bar{\eta}_K} e^{-\frac{\bar{G}_K}{\bar{\eta}_K} \cdot t}\right] \sigma_{eff}$$

with:

$\bar{\eta}_K = 2800$ d · MPa
$\bar{G}_K = 3700$ MPa
$\bar{\eta}_M = 119\,000$ d · MPa.

The stress exponent n for the material law according to MENZEL/SCHREINER was set to $n = 2.5$, in order to use the same value as that used when describing the relationship of the failure strain to the stress difference $|\sigma_1 - \sigma_3|$. The determination of the parameters K_B and n from the results of short-term triaxial extension tests on rock salt from the ASSE and ERSLEV (Denmark) deposits are shown in Figure 4. The relationship:

$$\epsilon_{1u} = K_B(\sigma_3 - \sigma_1)_u^n$$

can be used to determine the failure energy D for short-term tests with constant rate of load increase. However, because the results of the short-term tests are strongly dependent on the rate of increase of load, reliable determination of the specific plastic deformation energy with respect to unit volume is not possible. For this reason, for the purposes of the example, the following discussion will

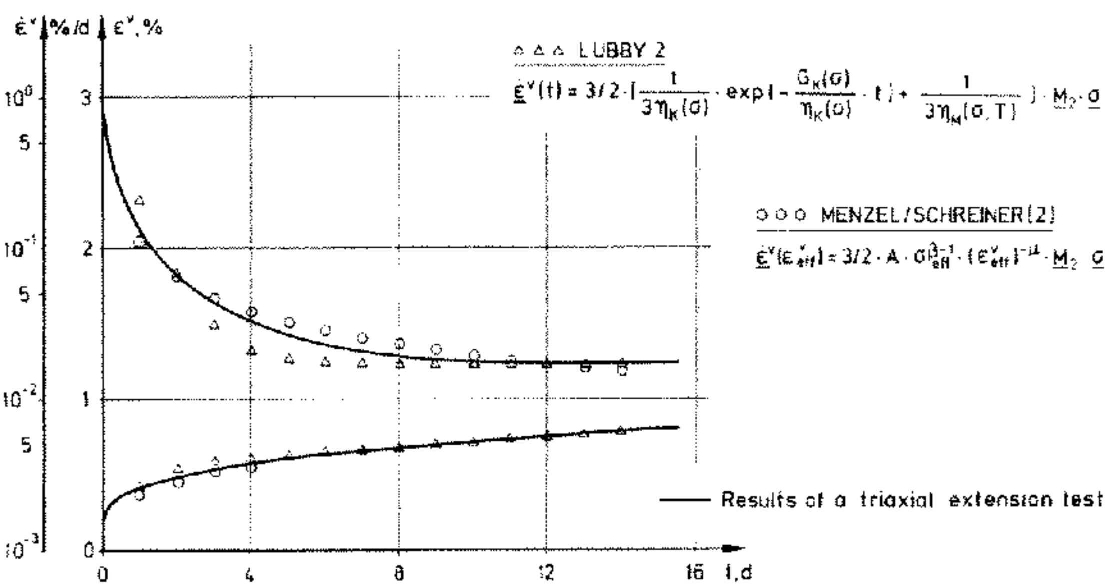

Figure 3. Curve-fitting with two different material laws

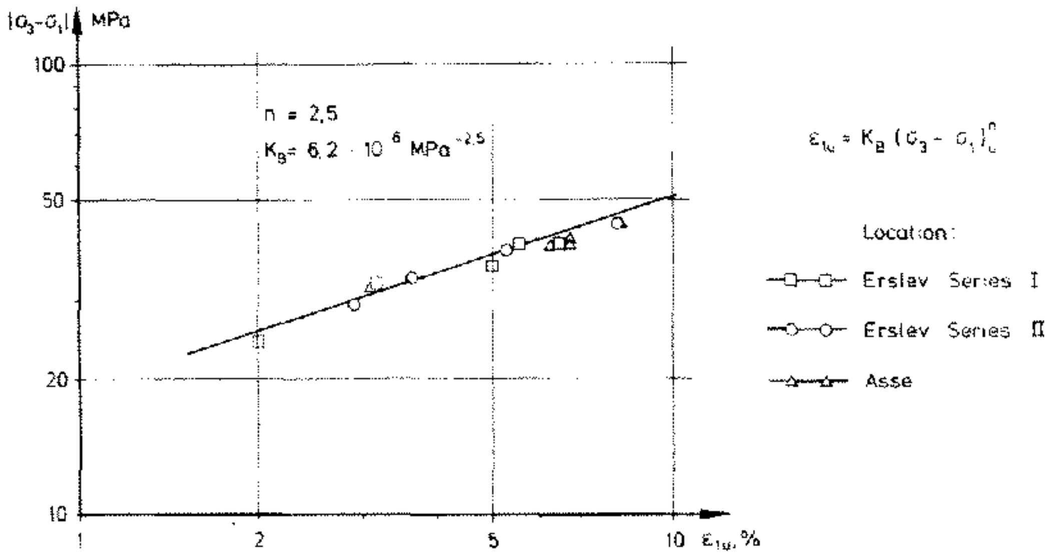

Figure 4. Determination of the Parameters K_B and n

assume the values D = 1 MN/m² and D = 5 MN/m². Using these values, the material law of MENZEL/ SCHREINER indicates a time to failure of $t_B = 43$ a and $t_B = 22\,100$ a, and the material law LUBBY 2 indicates a time failure of $t_B = 265$ d and $t_B = 4$ a, both for values of D = 1 MN/m² and D = 5 MN/m², respectively.

These results clearly show that the choice of material law has a decisive influence on the predicted time to failure. The considerable influence of the failure energy D is also apparent. A relatively precise prediction of the time to failure to be expected is not possible here, owing to the uncertainty with which D can be determined from short-term tests.

The Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover has obtained interesting results from creep rupture tests with triaxial compressive loading (Wallner, 1981). The results of the tests, which were regulated in accordance to strain, are schematically represented in Figure 5. The influence of various strain rates $\dot{\varepsilon}_{eff}$ and the average controlling stress σ_0 was investigated. The latter was kept constant within each test. For each average controlling stress σ_0, the results allow the boundary to be determined between stress conditions that lead to failure and stationary stress conditions that can be indefinitely accommodated without failure.

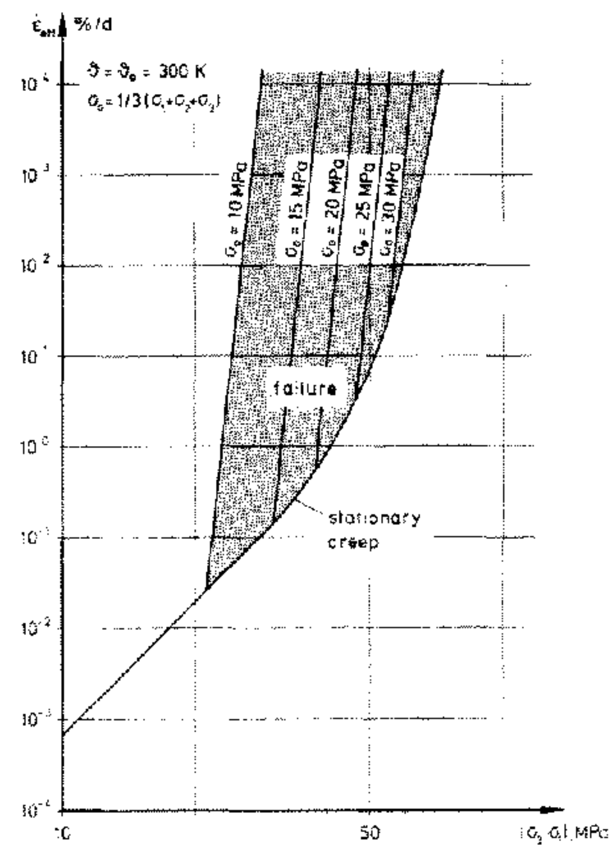

Figure 5. Test results obtained by the BGR (Wallner, 1981)

CREEP RUPTURE INVESTIGATIONS AT THE INSTITUT FÜR UNTERIRDISCHES BAUEN

In 1982, several creep rupture tests were carried out by the Institut für Unterirdisches Bauen on rock salt samples from the Asse and Erslev deposits. The tests were carried out under triaxial extension conditions, and the test durations varied from a few hours up to approximately 500 hours. The results are shown in Figures 6 and

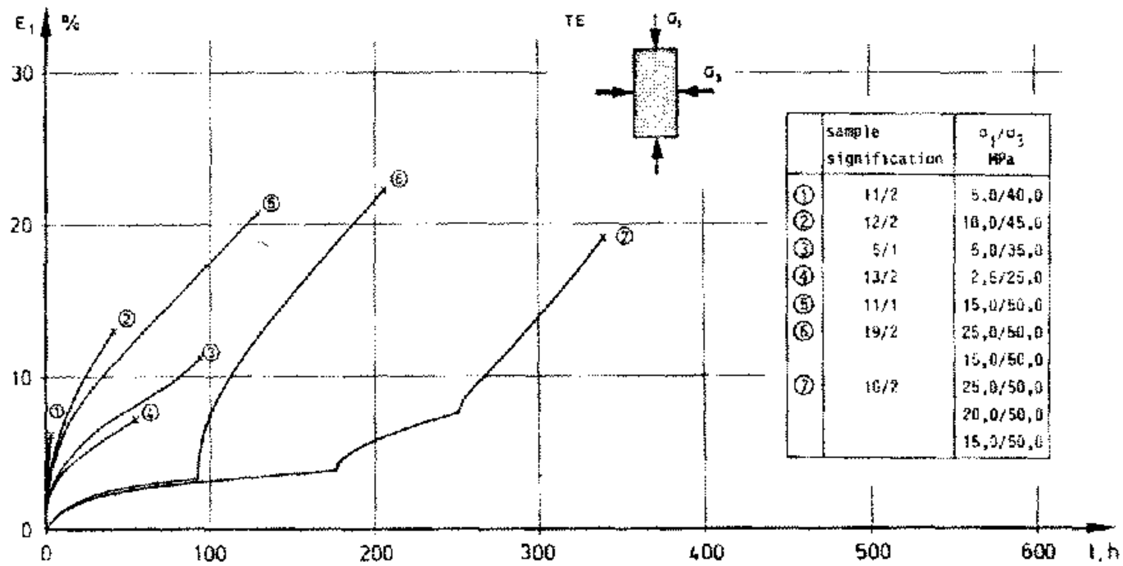

Figure 6. Results of Creep Rupture Tests, Location Erslev

7. Furthermore, in addition to the sample type, the figures indicate the stress conditions in each of the tests, e.g., the size of the axial stress σ_1 and the size of the confining pressure σ_3.

All tests were carried out with cylindrical samples of dimensions h/d = 180/90 mm. The very large failure strains that occurred are particularly noticeable. Even under the conditions of indirect tensile stress, they approached values of more than 20% the natural (logarithmic) strain. Furthermore, the considerable influence of the isotropic stress component on the time to failure, and the corresponding maximum strain, is also visible. For example five tests on samples from the Asse deposit were carried out with a differential stress of $|\sigma_1 - \sigma_3| = 35$ MPa and various axial stresses σ_1. Whereas the time to failure for test 19/1 ($\sigma_1 = 2.0$ MPa) was only approximately 7 h, test 3/1 ($\sigma_1 = 12.0$ MPa) required approximately 530 h until failure of the sample.

Evaluation of the few results of creep rupture tests carried out up to now are shown in double logarithmic form in Figures 8 and 9, which indicate the relationship between the time to failure and the ratio σ_3/σ_1 and the stress difference $\Delta\sigma = |\sigma_1 - \sigma_3|$. The influence of the isotropic stress component on the time to failure is indi-

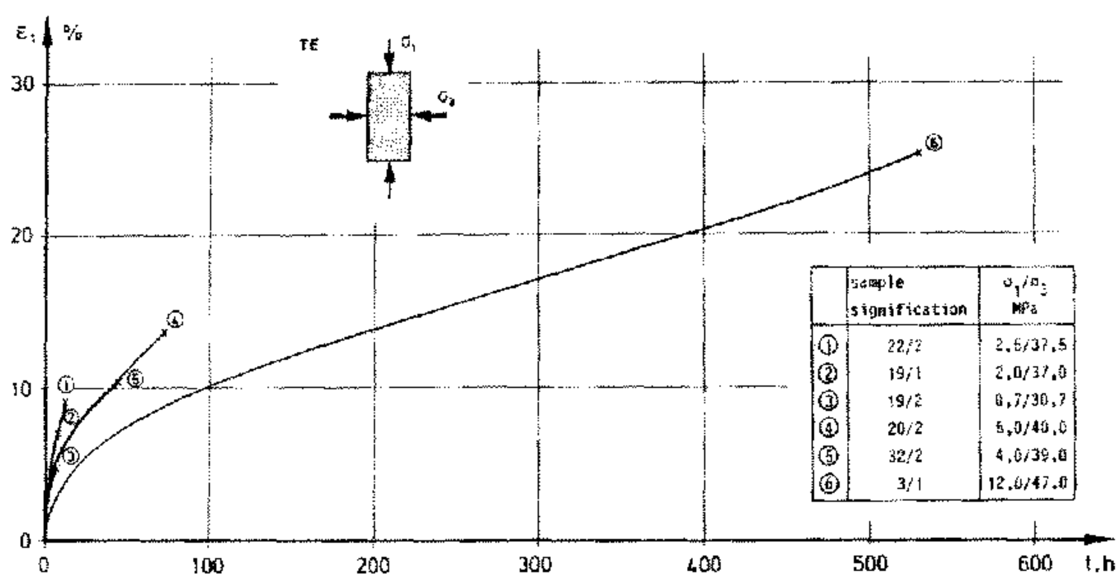

Figure 7. Results of Creep Rupture Tests, Location Asse

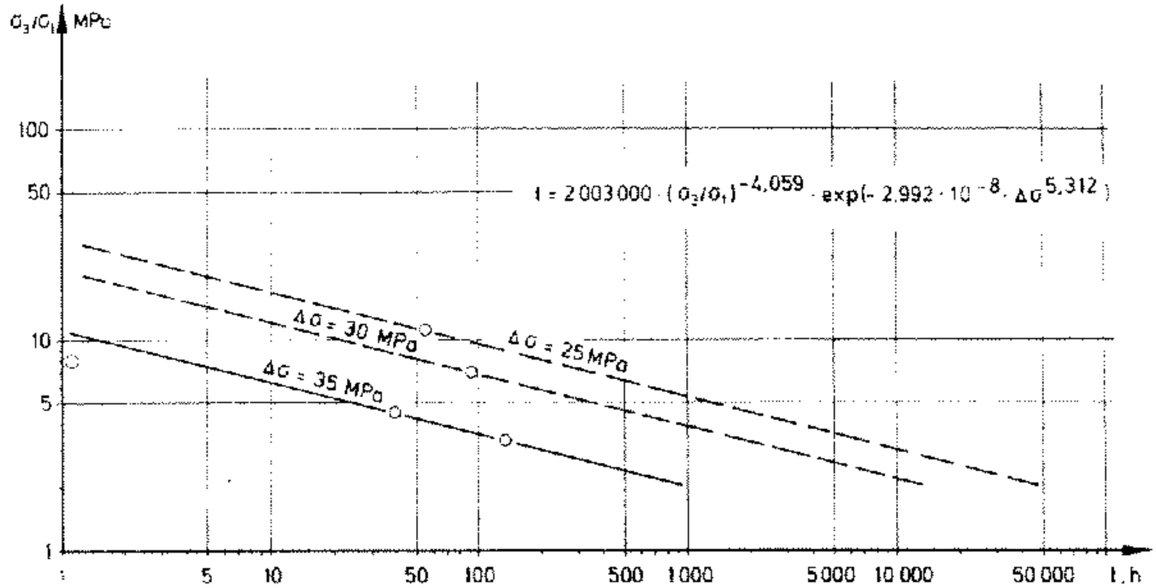

Figure 8. Results of Creep Rupture Tests, Erslev deposit

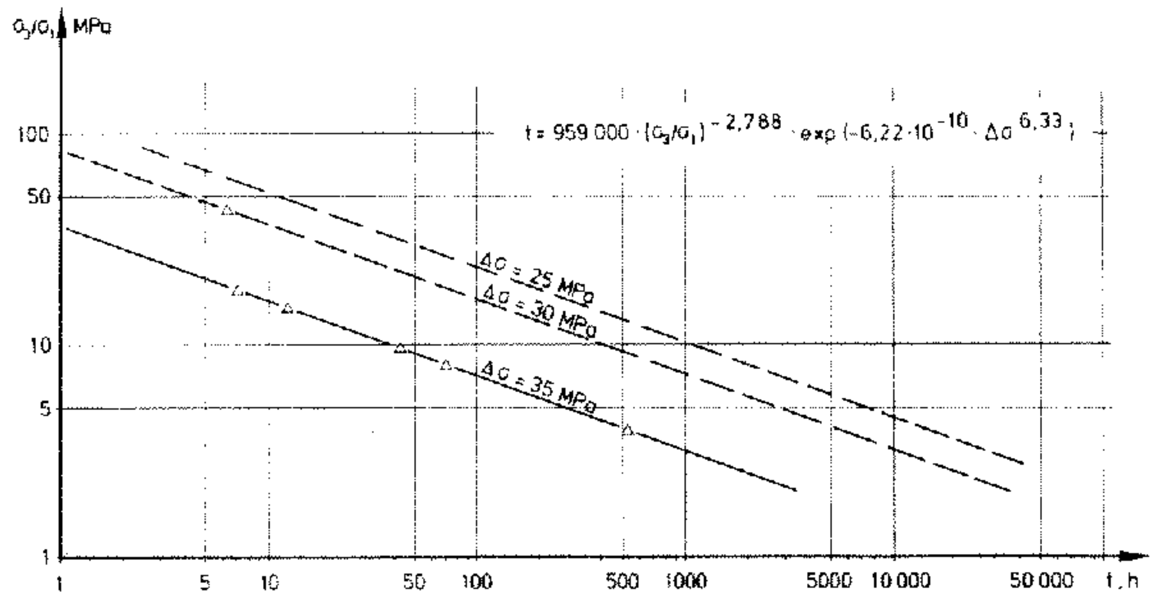

Figure 9. Results of Creep Rupture Tests, Asse deposit

cated by the ratio σ_3/σ_1 and the influence of the deviatoric stress component is represented by the stress difference $\Delta\sigma$.

The Figures 8 and 9 also show corresponding mathematical formulations. However, it should be noted that these figures can only be used as an indication of the phenomenological description of the creep rupture behaviour of rock salt. Further tests are necessary, particularly with respect to the dependency of the time to failure on the differential stress $|\sigma_1 - \sigma_3|$ for smaller values of $\Delta\sigma$ too. Furthermore, it is necessary to investigate the validity limits of the diagrams. For practical purposes, it appears possible to satisfactorily describe the creep rupture behaviour of rock salt at a particular location with 9 to 12 creep rupture tests at differing stress differences and ratios σ_3/σ_1.

These creep rupture diagrams then allow the construction of Mohr's envelopes, which describe the strength of the material with respect to time. Mohr's envelopes for rock salt samples from the Asse deposit are illustrated in Figure 10. The relationship between the time to failure and the maximum differential stress before failure is also

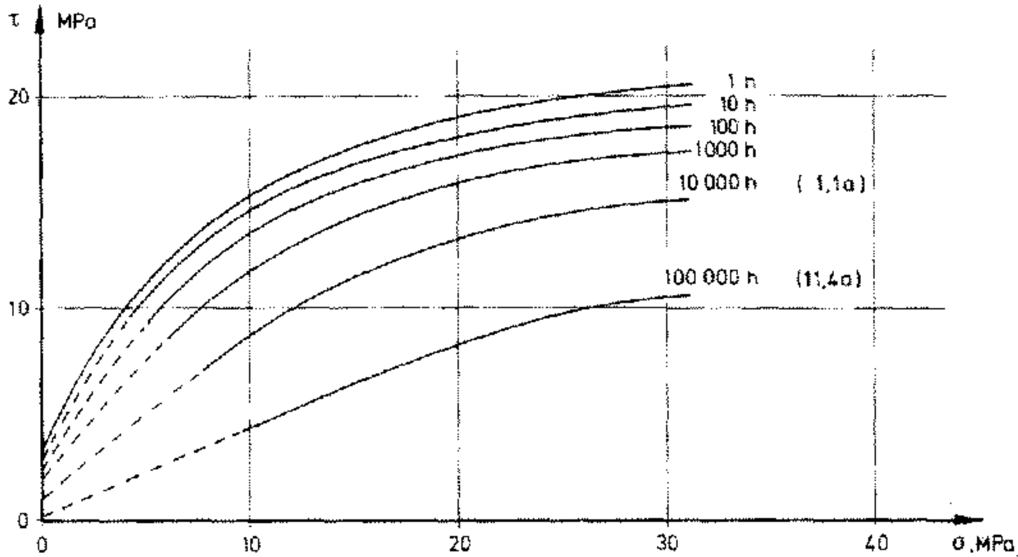

Figure 10. Time-dependent triaxial strength, Mohr's envelope

clearly visible. If, for example, the time to reach failure of 100,000 h (11.4 a) is required, then Figure 10 shows that the stress levels effective over this time period does not exceed approximately 40–50% of the short-term strength.

SUMMARY

To summarize, the results of this study show that even as few as 8 to 12 creep rupture tests, with test durations between 7 h and 600 h, are sufficient to allow an estimate to be made of the creep rupture behaviour of rock salt within the framework of rock-mechanical investigations.

ACKNOWLEDGMENT

We would like to thank Mr. R. Neumann for carrying out the laboratory work.

REFERENCES

Nair, K. and R. D. Singh. 1973. Creep Rupture Criteria for Salt. 4th Symposium on Salt, Houston (Texas), Vol. 2:41–50.

Menzel, W. and W. Schreiner. 1977. Zum geotechnischen Verhalten von Steinsalz verschiedener Lagerstätten der DDR. Part II—Neue Bergbautechnik 7.

Wallner, M. 1981. Analysis of Thermomechanical Problems Related to the Storage of Heat Producing Radioactive Wastes in Rock Salt. First Conference on the Mechanical Behavior of Salt, The Pennsylvania State University.

Lux, K.-H. and R. B. Rokahr. 1980. Dimensionierungsgrundlagen im Salzkavernenbau. Taschenbuch für den Tunnelbau (4), Verlag Glückauf, Essen.

Knoll, P. 1973. Beitrag zum Einfluß der Zeit auf die Verformung und den Bruch von Salzgestein. Freiberger Forschungshefte, A 528.