Results of Rock Mechanical Investigations for Establishing Storage Caverns in Salt Formations

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ABSTRACT

The Institute of Safety in Mines in Leipzig (GDR) has been working for more than ten years in the field of geomechanical research for the installation of cavern stores in leaching formations. Based on the example of the cavern store established in Bernburg, GDR, the paper presents the results of theoretical calculations, petrophysical laboratory tests and in situ measurements.

From the results of study, there are derived statements on cavern stability safe operating conditions under the aspect of rock mechanics, as well as on cavity convergence in the time and cover rock movements resulting from it.

INTRODUCTION

The storage of liquid and gaseous energy sources is a point of focal interest to the national economy of the German Democratic Republic. A high proportion of importation, transport over long distances between producer and consumer, as well as great fluctuations of need between night and day, working days and Sundays, summer and winter make it necessary to have stores of high capacity assuring short access times and high output performances for a stable supply of these energy sources to the national economy. Besides from storage in worked-out gas pools and oil deposits, in aquiferous structures as well as in existing mine excavations, storage in leached brine caverns takes a decisive part in the German Democratic Republic. The nation has available thick rock salt formations, which are favourably situated to the consumption centres and give the possibility of leaching caverns in the order of 10^5 to $10^6 m^3$ of cavity volume. By an ingenious coupling of cavity leaching with the production of rock salt brine used for the extraction of soda, chlorine and white salt, it is possible to obtain advantageous economic effects in making salt cavern stores.

For more than ten years, the Institut für Bergbausicherheit has been working in the field of rock mechanical research for the construction and operation of salt cavern stores. The present contribution is intended to explain the problem related to rock mechanics, the elaborate investigation method and the result of rock mechanical laboratory and in situ tests, as well the parameters derived therefrom for the construction and the operation of caverns.

DETAILS OF THE UNDERGROUND STORE AT BERNBURG

History of the Store

In 1968, planning activities for the construction of the underground storage at Bernburg were first begun. The first ten drill holes were put down in the period from 1969 to 1971. They were immediately designed and installed as operating wells. The leaching process for cavity making started at two caverns in December, 1970. The construction of surface establishments such as the compressor plant, pressure control measuring station, control centre and social facilities was carried out in the period from 1971 to 1975.

The first operations were begun on 31 January 1974. By 1981, 14 caverns had been finished and put into operation. The useful cavity volumes were between 10^5 and $3 \cdot 10^5 m^3$. Sections through model storage caverns are shown in Figure 1. The underground store of Bernburg may be termed "a battery of gas cavern stores." The individual caverns are interconnected in groups of two and three caverns. Well installation is adapted to features that are characteristic to the operation of gas caverns. All technical plants are planned so as to assure high effi-

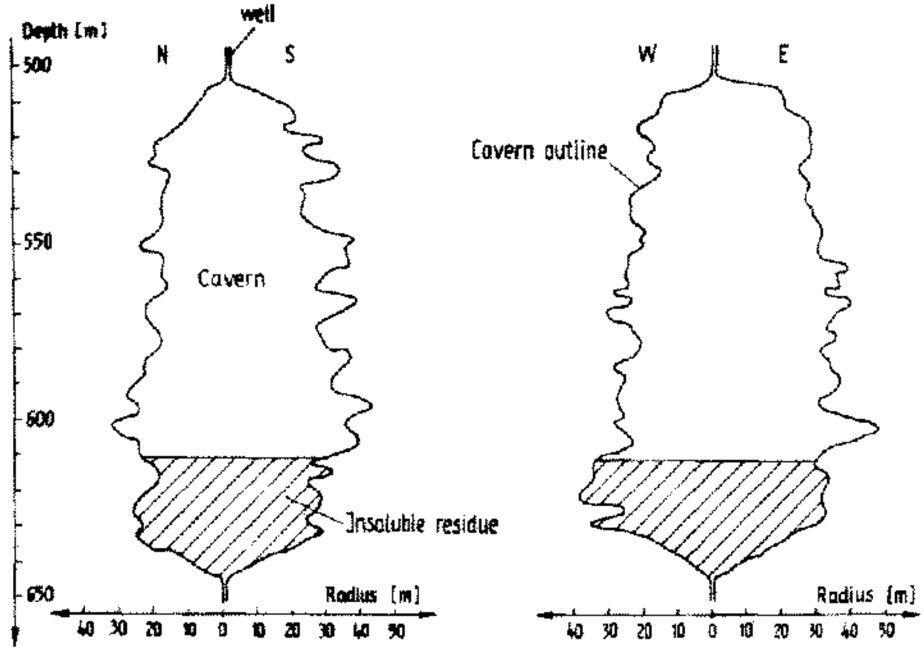

Figure 1. Vertical sections through a leached gas storage cavern—Underground gas storage facility at Bernburg.

ciency and flexibility of operation. Starting and change-over from the feeding to the emptying of the caverns, respectively, can be done within one hour.

The variation of storage pressure in a cavern during a period of 5 years, clearly reflecting the seasonal peak loading character of the underground storage at Bernburg is shown in Figure 2. The storage volume can readily be expanded, by means of connecting additional caverns.

Geological Condition

The storage facility at Bernburg is situated in the crest area of the Bernburg anticline. This anticline is a Hercyn-

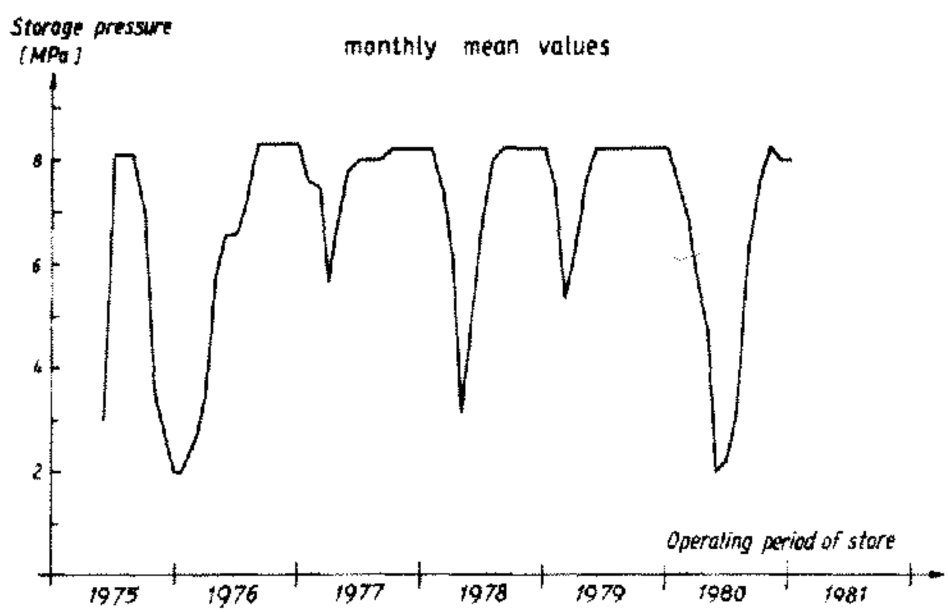

Figure 2. Mode of operation of the storage pressure of a cavern in the underground gas storage facility at Bernburg.

ian salt structure of the Upper Permian (Zechstein) in the north of the Halle-Hettstedt strata bridge, and extends over some 30 km^2. The anticline developed during the Kimerian stage of the Saxonian orogenesis. Salt migration took place to the south; hence, salt thickness decreases from north to south. Within the region of store, strata conditions are uncomplicated. The Upper Permian bedding is mostly horizontal without any reported folds. In the area of Bernburg, the Straßfurt series is the dominating part of the Upper Permian with rock salt thicknesses ranging from 200 m to 500 m. They are encountered at a depth of 200 m to 700 m below the surface. For the construction of caverns, the depth from 450 m to 650 m is utilized.

ROCK MECHANICS INVESTIGATION PROGRAMME

Aim of Investigations

Rock mechanics investigations were carried out with a view to specify conditions and parameters from the rock mechanical aspect for the construction and the operation of cavities, so as to assure their use without disturbances throughout long periods. This required answers to the following problems:

- Suitability assessment of the rock salt deposit from the rock mechanical point of view for the installation of underground gas store (UGS) on the basis of geological, geophysical and geohydrological data, as well as of the results obtained from rock mechanical investigations
- Stability assessment of storage caverns and storage systems with consideration of the working conditions of storage
- Determination of dimensioning parameters to be observed, such as size and shape of the cavern, minimum roof and floor pillars in compact rock salt, minimum admissable spacing from wall to wall of adjacent caverns in the storage field
- Determination of operating parameters to be observed, such as maximum and minimum operating pressure and operating pressure change-frequencies, respectively, as well as minimum pressures to be kept on the changeover and the reconstruction activities over limited periods;
- Precalculation of potential losses in storage volume during the time of operation
- Precalculation of potential effects exercised upon the surface by cavity creation and storage operation (i.e., subsidence and collapse).

For solving and evaluating these tasks and problems, there was developed an investigation method, which proved useful for the solution of rock mechanical problems in salt mining and in cavern storage throughout many years of application.

According to this method, a complex rock mechanical investigation programme is carried out for the purpose of assessing suitability of the salt rock deposit as a rock salt cavern. Besides, from the analysis of recorded geological data (depth, stratigraphy, petrography, mineral analysis), tectonic and geohydrological data (tectonics, microtectonics, jointing, gas- and water-carrying content, gas and water permeability), the programme made provisions for extensive laboratory tests on the state of strength, deformation and stress of the rock. It also provided for tests in underground and surface drill holes, with a view to determine the stress-strain state of the deposit as well as to measure and to observe the operating caverns for the purpose of verifying in practice the predicted convergence behaviour and surface effects. All characteristic data determined for rock and deposit underlie the stability evaluation of caverns on the basis of numerical and analytical calculation models. The experimental and theoretical fundamentals were already published several years ago (MENZEL et al., 1974–1978).

Rock Mechanical Laboratory Tests

Rock mechanical laboratory investigations were conducted on core material from prospect and cavern drill holes, respectively, and on material from the adjacent rock salt mine at Bernburg-Gröna.

The investigation range of the different test methods is shown in Figure 3. Measurements were made in the areas of roof, cavern sky, cavern and floor pillar. Prestressing and other damage of samples have been avoided by the limitation of drilling pressure, careful sampling and handling of core and moisture-proofing of samples that have been obtained.

Strength and deformation behaviour are determined on cylindrical test specimens of 40 mm diameter and of 80 mm height. Strength behaviour is determined in short-term tests at a constant rate of loading (500 MPa/h) under uniaxial and rotationally symmetrical triaxial compression within the confining pressure range of 0.5 to 25 MPa with 8 confining pressure stages on about 10 test specimens each. Therewith, the stress-strain diagram of the sample is recorded up to the point of fracture. Tensile strength is derived from uniaxial tensile tests, Brazilian tests and beam bending tests.

The triaxial strength behaviour of adjacent rock salt is represented in Figure 4. It is given as a function of the critical loading duration, and a comparison is made between the determined short-term strengths and the long-term strengths derived from long-term tests.

The adjacent salt rock is of comparatively low to medium strength. In the roof area of the deposit (200 to 400

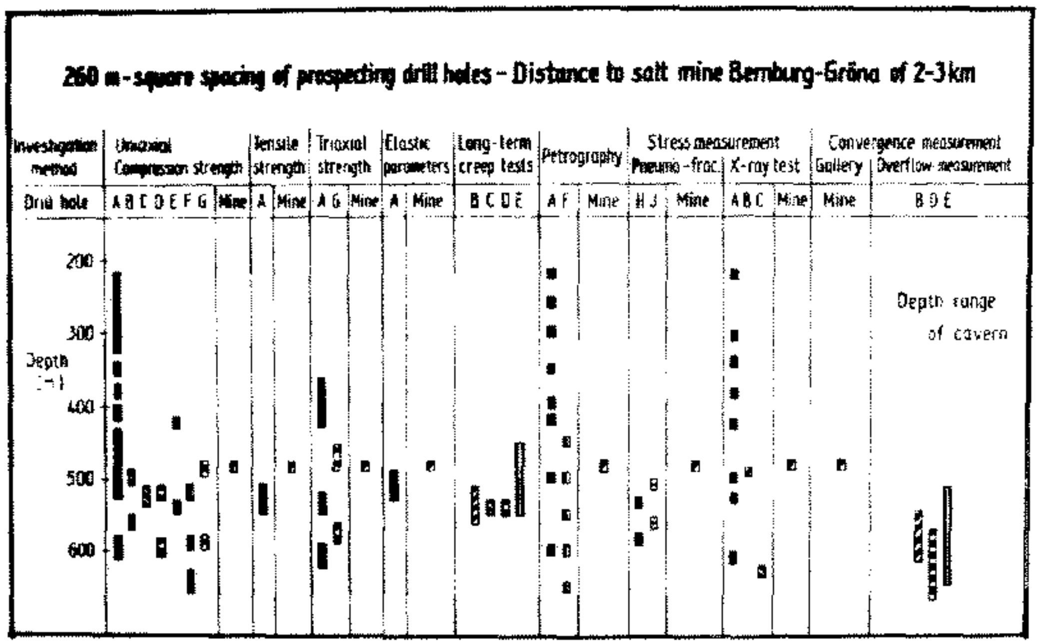

Figure 3. Rock mechanical investigation programme of the storage field at Bernburg.

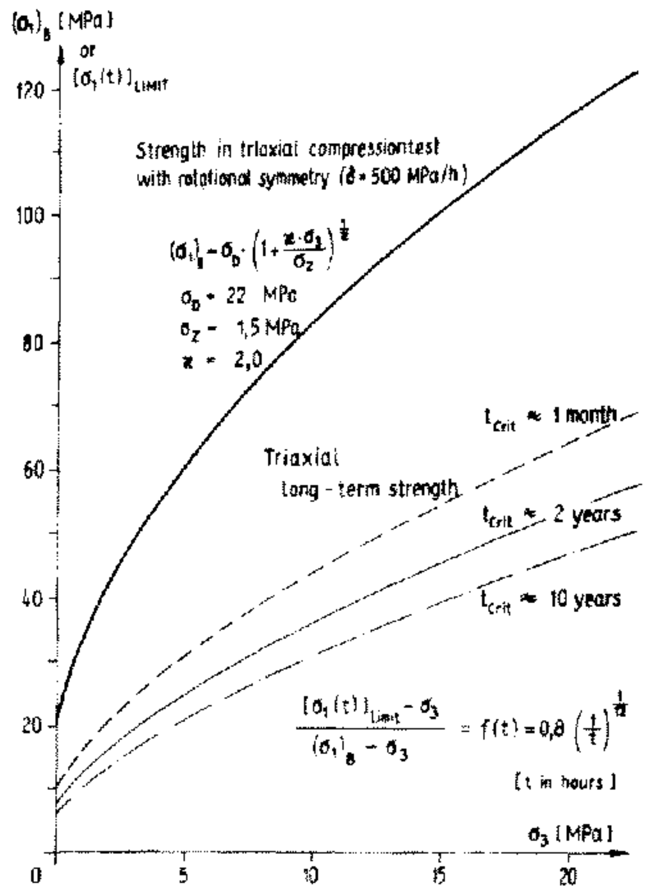

Figure 4. Triaxial compression strength of rock salt.

m), strength of the adjacent salt rock clearly exceeds that of the cavern area. The causes of strength differences between the roof and the wall, can be derived from the petrographical tests and are a result of the fabric, the mineralogical composition and the tectonic loading of the rocks.

The triaxial strength behaviour is described by the relation of maximum and minimum principal stress on the occasion of fracture in the following way:

$$(\sigma_1)_B = \sigma_D \left(1 + \frac{x\,\sigma_3}{\sigma_Z}\right)^{1/x}$$

with

$$\sigma_D = 22 \text{ MPa} \qquad \sigma_Z = 1.5 \text{ MPa} \qquad x = 2.0.$$

The σ-ϵ curves of rock salt at constant loading rate are shown in Figure 5. Statically, the elasticity parameters are derived from the stress-strain diagram of intermediate stress relief under uniaxial and triaxial stress states. Dynamically, the elasticity parameters are determined from the velocities of measured longitudinal and transversal ultrasonic waves.

The deformation behaviour over time and the rheological properties were determined on test specimens by means of long-term tests at constant load over a period of at least 8 weeks. The test series covers tests under uniaxial compression at different loading stages within the range of 15% to 85% of the short-term strength. Tests also were run under rotationally symmetrical and triaxial compression at confining pressures amounting to the scheduled minimum and medium operating pressures at different loading stages within the range of about 10% to 65% of the short-term strength.

Creep curves at various loading stages are shown in Figure 6. Deformation parameters are derived from the tests both at constant rate of loading and also at constant load.

Deformation is composed of two parts, an elastic and a creep deformation portion. The elastic portion is non-linear and stress-dependant with

$$E = E_0\left(1 + \frac{\sigma_3}{\sigma_0}\right)^2$$

$$E_0 = 2\ \text{GPa}, \qquad \sigma_0 = 6.3\ \text{MPa}.$$

The creep deformation portion follows a power law with

$$\epsilon = K \cdot \sigma^n \cdot t^m, \qquad K = 2.5 \cdot 10^{-5} \quad [\sigma \text{ in MPa, t in h}]$$

$$n = 2\,{}^{1}/_{7} \qquad m = {}^{1}/_{7}$$

The coefficient of stress relaxation is exponentially dependent on the loading duration:

$$K_t = \frac{2}{1 + \exp[t^{-0.2}]} \qquad [\text{t in h}].$$

The strength quotient through time results from the acting principal stress differences at fracture and at the critical loading duration with

$$\left[\frac{(\sigma_1 - \sigma_3)_{\text{LIMIT}}}{(\sigma_1 - \sigma_3)_B}\right] f_t = 0.8\left(\frac{1}{t}\right)^{1/12} \qquad [\text{t in h}].$$

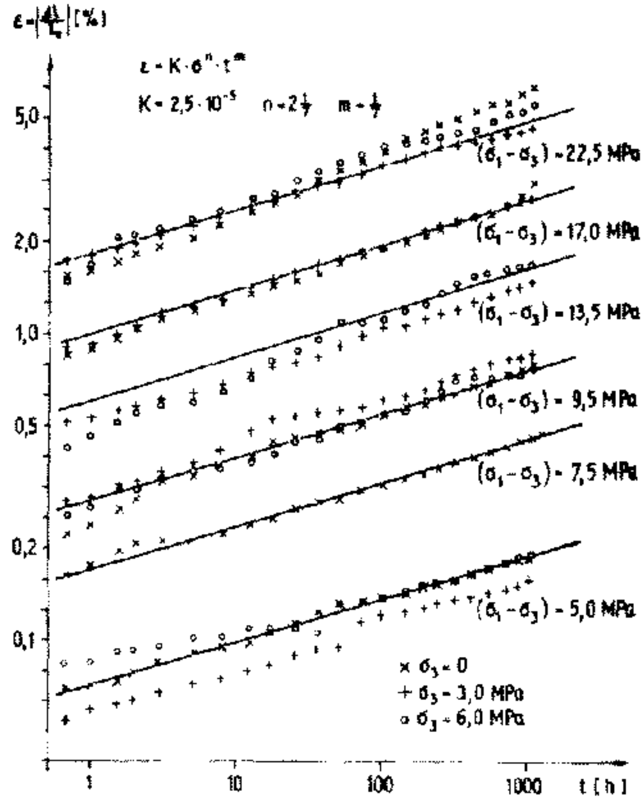

Figure 6. Creep curves at different loading stages.

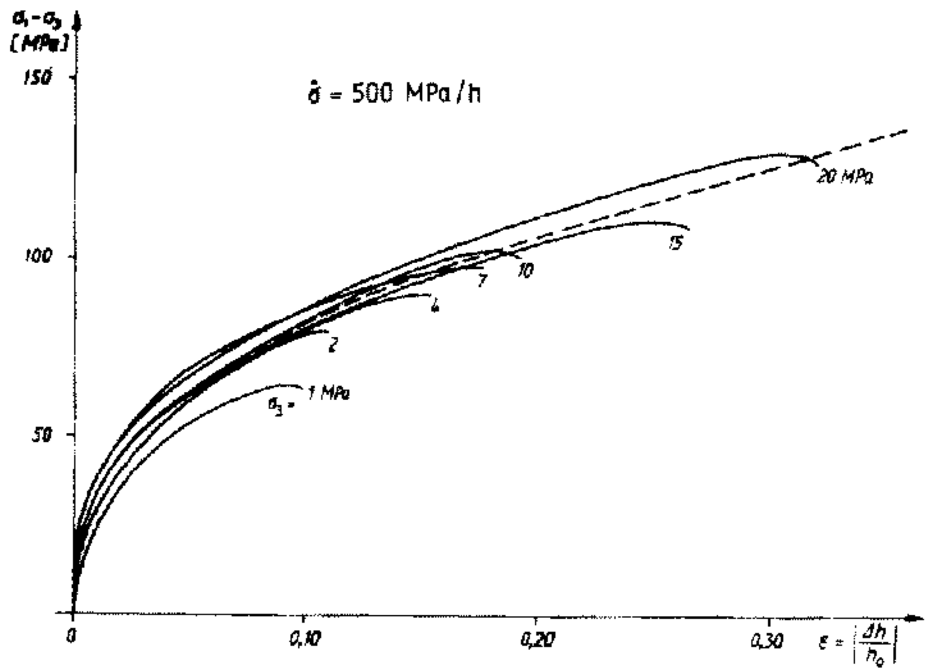

Figure 5. Stress-strain-diagram.

For the purpose of assessing the stress of the deposit and the local state of stress around the deposit, cores were taken from two different depths of the deposit (roof pillar or sky area and cavern region). About 50 to 100 cleavage crystallites from each sample are employed for the determination of X-ray interference fringes distribution.

Analysis of the measured width of X-ray interference fringes yields data which is predictive of the natural prestressing of rock salt in the deposit.

The measured principal stress differences are illustrated in Figure 7. They suggest little prestressing of the material and an approximately hydrostatic local stress state with a lateral pressure coefficient $\lambda = 1$.

Measurements in the Deposit

For the purpose of verifying the deformation measurement results obtained in the laboratory, convergence measurements were carried out in galleries of the adjacent mine at Bernburg-Gröna. These galleries, driven by headers in advance of the stope face, were 3 m in diameter. Convergence measurement was done at four azimuths—horizontally, vertically and in each case at a dip of 45°. At a depth of 485 m, continuous observation of two such cross-sections were made over a period of two years. The derivations in the various measuring directions are so insignificant that it is useful to report all measuring cross-sections and azimuths. The measured convergences are illustrated in Figure 8. After 23 months, maximum values were between 25 and 30 mm at the various azimuths. The curve shape is easy to describe by the strain-hardening theory.

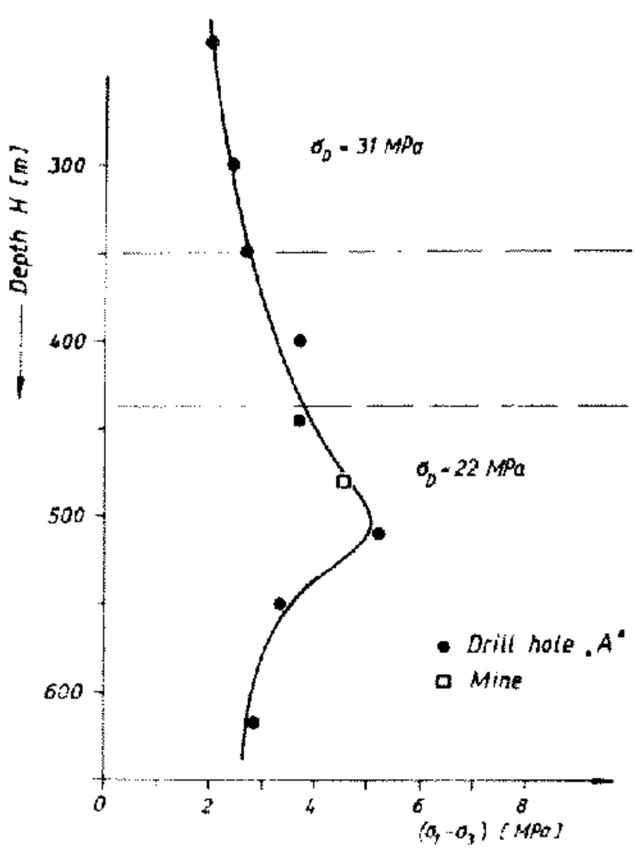

Figure 7. Connection between depth and principal stress difference.

In order to determine the acting pressure and to get evidence of gas pressure applicability and of salt rock tightness, pneumatic and hydraulic fracturing tests were carried out in mechanized headings and in prospecting boreholes within the region of depth intended for storage. The method and measuring procedures were described by Förster *et al.* (1981, p. 292). Measuring boreholes were run horizontally to a depth of 10 m. In Table 1, breakdown pressures and shut-in pressures are gathered as a function of the packer-bearing depth.

The curve of shut-in pressure in comparison with the calculated radial stress around a circular gallery is shown in Figure 9. For spacings of more than 5 m, a pressure of 10.6 MPa was determined. This approximately corresponds to the lithostatic pressure. The measured results are gathered in Table 2. Shut-in pressure coefficients slightly exceed those obtained from underground boreholes. The results of hydrofracturing tests confirm the assumption that there is a hydrostatic basic stress state amounting to the value of the lithostatic pressure due to depth.

Derivation of Dimensioning Parameters

Stability assessment of caverns and derivation of dimensioning parameters are done on the basis of the mathematical and mechanical analysis of the stress-strain state existing in the adjacent rock around the storage cavities. Use was made of analytical and numerical calculation models involving rock mechanical behaviour, cavity geometry and deposit structure, as well as the basic stress state in the rock and operating storage pressure as essential entry parameters. Details of the calculation models were already reported by Menzel *et al.* (1974, p. 272) and by Menzel, Schreiner *et al.* (1978, A 598). From these models, the following results were derived:

1. From the rock mechanical point of view, leached and rotationally symmetrical cavities with a vertical axis, a height-diameter ratio of 2 to 3 and a spherical cavern sky shape are the favourable solution to gas storage in the deposit of Bernburg. Cross-sectional surfaces of 3,000 m^2 (diameter of about 6 m) proved to be efficient with respect to leaching technique control and to rock mechanical conditions for cavity stability.

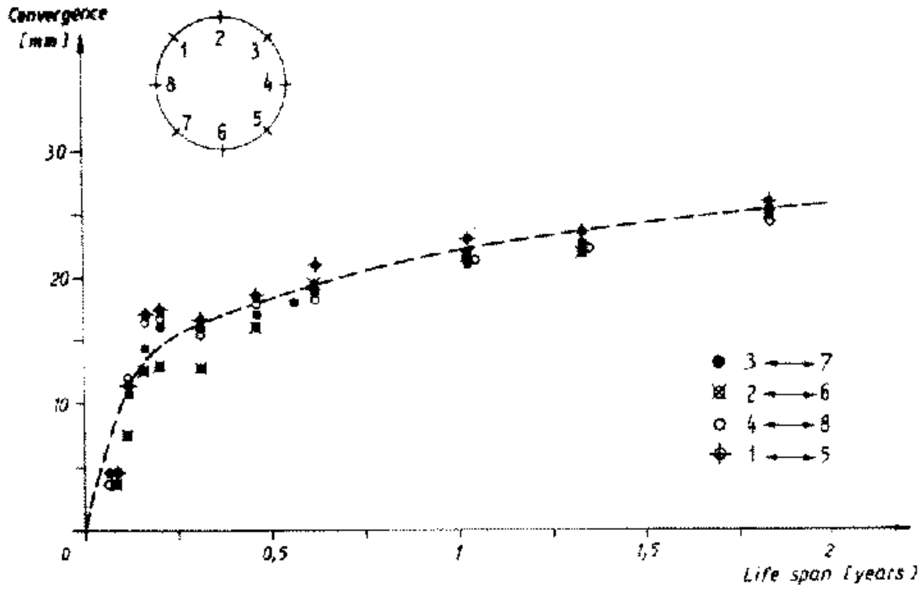

Figure 8. Convergence of an underground gallery.

TABLE 1
Results of Hydrofracturing Tests in the Bernburg-Gröna Mine

Spacing to wall m	Breakdown pressure MPa	Shut-in pressure MPa	Shut-in pressure coefficient
1.0	9.5	6.3	1.32
2.5	11.2	9.3	1.96
5.0	12.6	10.5	2.21
5.9	12.3	10.7	2.25
7.3	12.5	10.6	2.23

2. On dimensioning rock salt pillars needed in the roof and the floor, it was realized that tight sealing of storage cavities cannot be assured, unless deformation of roof and footwall is free from fracture. Gas caverns are dimensioned so as to prevent roof pillars from collapsing in the case of the drop of internal pressure to zero. On dimensioning the roof pillar, the medium height of the cavern sump, compactly stowed by consolidating residues, can be added as well. Roof pillars of 75 m and floor pillars of 50 m turned out to be necessary for cavern depth regions from 500 to 650 m.
3. Minimum spacing between caverns within the storage field is determined under the premise that support pillars are stable and responsible for assuring full load-bearing capacity for overlying rock load throughout the working period. For these calculations, the Institut für Bergbausicherheit applied the

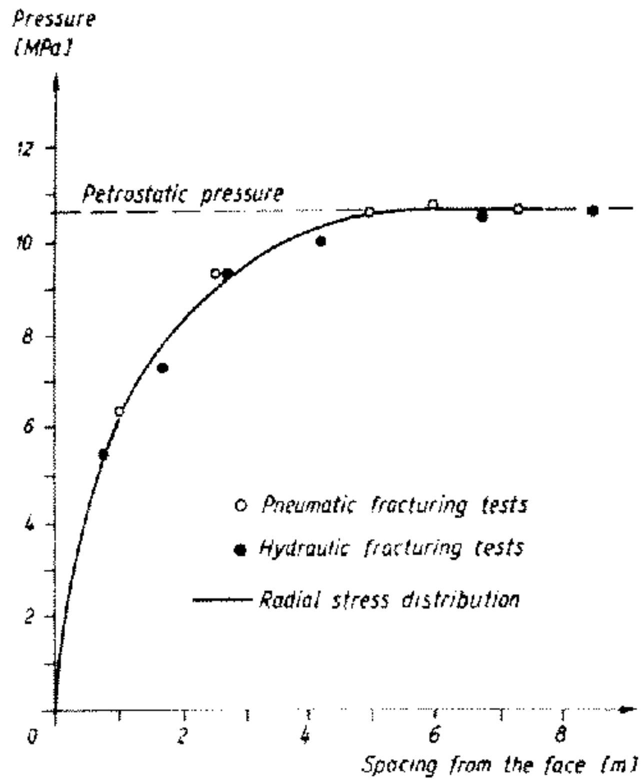

Figure 9. Minimum stress values measured around a gallery on hydrofracturing tests.

TABLE 2
Results of Hydrofracturing Tests in Deep Drill Holes at the Cavern Field

Depth range m	Breakdown pressure MPa	Shut-in pressure MPa	Shut-in pressure coefficient
533–536	13.7	12.8	2.45
593–596	18.7	14.2	2.44
633–636	17.0	15.3	2.46

theory of boundary equilibrium with consideration of the long-term behaviour, which is already being used with good success in the determination of pillar-bearing capacities of stable mine workings in potash and salt rock mining. Maximum cavern heights up to 150 m require a minimum spacing of 100 m from wall-to-wall of adjacent caverns, as it becomes evident from the calculations.

The operating safety of the storage facility depends to a large extent on the stability of cavity outline. Rock mechanical evaluation begins from the premise that the pressure conditions in the cavern have to be maintained in such a state that progressive fissuring is excluded. This is intended to avoid to a large extent far-reaching fracture phenomena that may result in a loss of stability and tightness. Under these conditions, the storage at Bernburg needs a minimum pressure of 1 MPa for summary life spans of several months up to some years.

On determining the maximum operating pressure, the underlying principle is that pressure loading must not cause fracturing either of roof and floor pillars, nor of boundary pillars to adjacent caverns. With the said pillars being correctly dimensioned, the uncased cavern neck constitutes the critical area in the calculation of the maximum permissible gas pressure. Therewith, the change of the minimum principal stress in the rock due to cavity influence must also be taken into account.

A value of 1.1 has proved to be sufficient as safety coefficient between the acting minimum principal stress and the maximum permissible pressure as a result of the fracturing tests in the practical trial service over several years. This consequently results in a maximum permissible operating pressure depth gradient of 20 kPa/m for caverns of the first completion stage with uncased cavern neck lengths exceeding the cavern diameter.

Convergence behaviour is precalculated with consideration of the typical loading phases conditioned by the different technological processes in the construction and the operation, which are cited below:

- leaching phase with well head pressure
- service life phase at bring pressure
- tightness control and emptying at maximum storage pressure
- placing of covering agent and lining of brine ascending pipe at 1 MPa
- storage phase.

Figure 10 shows the result obtained from the calculation of convergence on the basis of the strain-hardening theory. As it becomes evident from Figure 10, an essential proportion of volume convergence takes place during

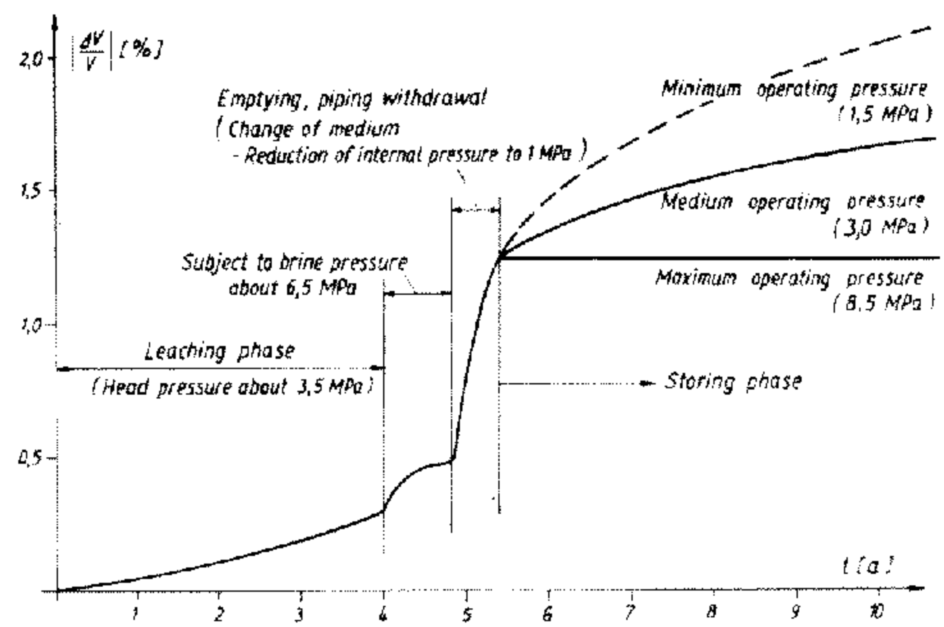

Figure 10. Calculated volume convergence of a cavern at an intended mode of operation.

the changeover phase of the leaching cavern. At the beginning of the storage phase, the volume convergence achieved the value of 1%. It will not exceed maximum values of 3%, provided that the mode of storage operation is maintained during the operating life span.

Results of In-situ Measurements on Caverns

With a view toward verifying that the applied rock mechanical calculation procedures and evaluation criteria are correct, various rock mechanical supervising measurements were carried out at the underground gas storage facility of Bernburg.

For the purpose of checking underground cavities for deformation behaviour, overflow volume measurements were carried out at brine-filled caverns, and from convergence measurements in mechanized headings at the mine Bernburg during the construction phase of the storage facility.

Figure 11 shows the overflow rates measured on two caverns after different life spans under brine pressure at different leached volumes. The good conformity of convergence measurements under different conditions with the calculation results confirms that the applied calculation procedures are correct.

With a view toward supervising the outline stability under minimum operating pressure, geoacoustical measurements were carried out at a cavern. During the observation period of several weeks, acoustic signals of fracture processes or larger falls of ground could not be

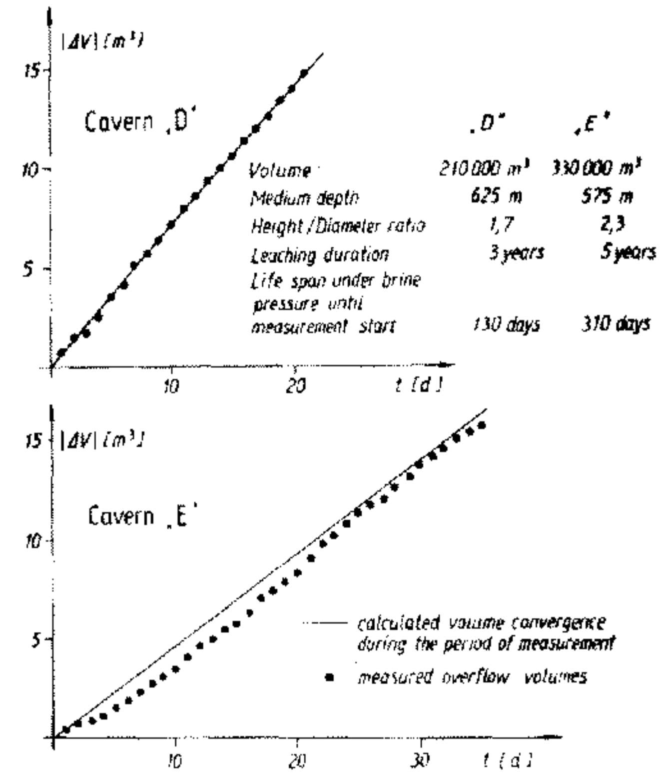

Figure 11. Overflow-measurements on brine-filled caverns.

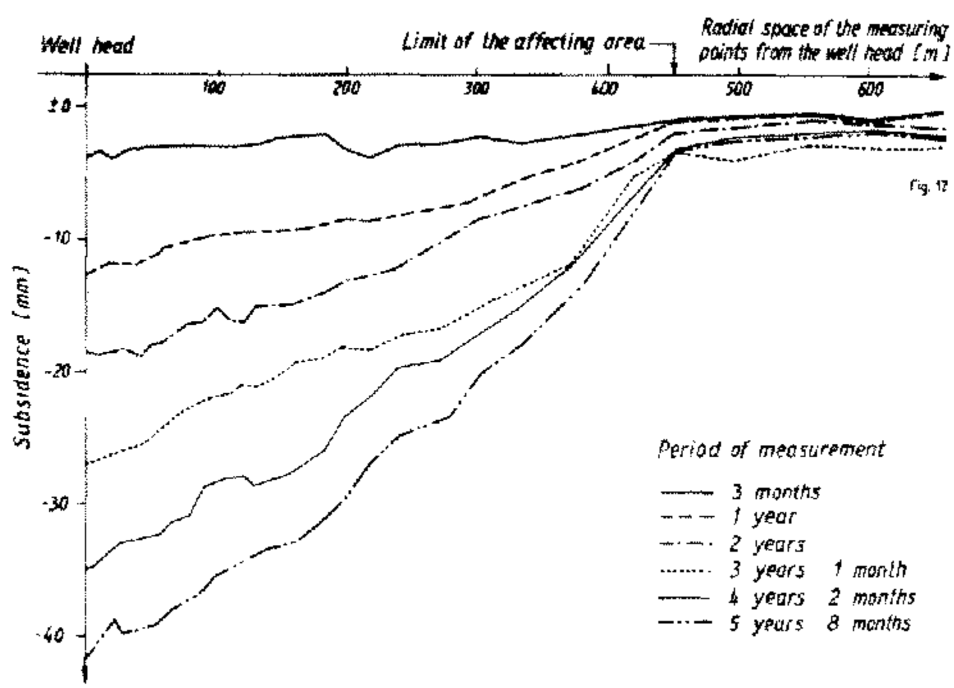

Figure 12. Measured subsidence trough above a gas storage cavern.

recorded. Underground cavern convergences result in a burden deformation originating from the cavern environment and progressing toward the surface. The time function of burden deformation generally differs in appearance from the volume convergence. With a view toward observing the underground subsidence sequence and supervising mining damage, a precise leveling system was installed and has till now been observed for more than 6 years during the construction and the operation of the caverns (Figure 12).

SUMMARY

This report gives a survey of the methods and results of rock mechanical investigations at the cavern storage facility of Bernburg. By the application of rock mechanical research results to the construction and operation of this underground store, it was possible to make an essential contribution to the safeguard of safety in mines and to the efficient utilisation of the store field. The operation running free from disturbances for about 10 years by this time confirms that the storage parameters specified from the rock mechanical point of view and the prognoses established by convergence behaviour are correct.

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