Mechanical Behavior of a Gas Storage Cavern in Evaporitic Rocks

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ABSTRACT

After completion of the first gas cavern in Germany (storage well Kiel 101) extensive measurements and experiments on rock behaviour were carried out. Moreover, in a series of stress and strain cycles in the cavern carried out as extended time tests the first appearance of fracturing and the elastic and plastic behaviour of the wall rock could be measured and mathematically explained. Hitherto available laboratory data were complemented by the in situ data. In particular the in situ data provided a reliable basis in determining the admissible operating conditions for the storage cavern.

INTRODUCTION

The first gas cavern project in Germany was started in 1965. A cavern for the storage of a gaseous medium is subjected to considerable stresses as the cavern (like a high pressure tank) is operated between a minimum and a maximum storage pressure. Establishment of the admissible pressure limits and the stress rate plays a decisive role in the economics of the entire project. Until now, these limiting values for large projects were based on laboratory tests only. Different theories used for the scaling often led to different results. In the Kiel storage project, the essential measurements were made on the completed cavern, and the mechanical behaviour of the wall rock and the admissible operating conditions were derived from these results. Thus conclusions could be drawn on the scaling of laboratory data and the applicability of certain theories.

The cavern was constructed for Stadtwerke Kiel AG. The geological and technical planning and the actual construction was carried out by EDELEANU GMBH FRANKFURT-HAMBURG. Details on the operation and further explanation of the basic conditions are in press for the International Gas Congress, Nizza 1973 (Kühne et al., 1973). The following details are confined chiefly to the rock mechanical behaviour during the construction of the cavern.

DESCRIPTION OF THE CAVERN

Geophysical investigation combined with economic considerations led to the location of the cavern 8 km south of the Bay of Kiel ("Kieler Förde") (Fig. 1).

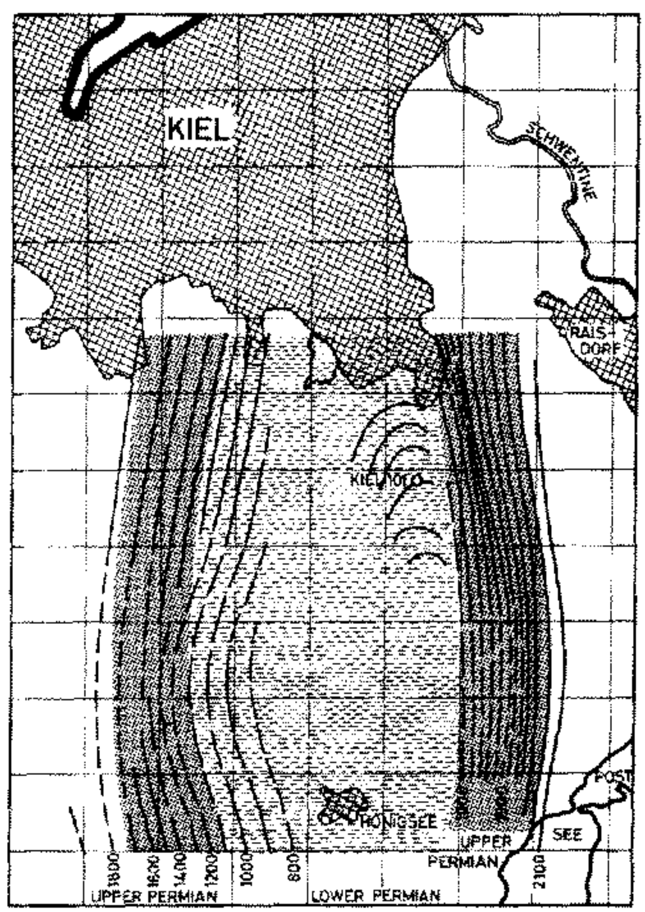

Figure 1. Salt Dome with Location of Storage Structure Map Base Upper Cretaceous.

The storage well was drilled through the following strata:

117.5 m	Quaternary
813.0 m	Tertiary
1,121.0 m	Upper Cretaceous
1,125.0 m	Lower Cretaceous
1,183.0 m	Lower Permian (Red Residual Clay)
1,351.5 m	Lower Permian "Haselgebirge" Salt with 22% red clay
1,500.0 m	Upper Permian (Rock Salt)

The cavern was leached between 1,305 m and 1,400 m depth. For this purpose the storage well was cased with 13 3/8" pipe to 1,304.8 m. This casing string was then protected against corrosion by a further 9 5/8" casing at 1,265 m. The annulus between the two casings was closed at 1,265 m by a special linear hanger with packer seal (Otis-Hanger) and was filled with oil up to the casing head (Fig. 2). As a consequence of the high sediment content of 22 vol %, only about 50% of the leached volume could be used while the rest was filled with insoluble material. For rock mechanical considerations the total capacity of 68,000 m^3 rather than the net capacity of only 39,600 m^3 must be taken into account.

DESCRIPTION OF ROCK MECHANICAL INVESTIGATIONS

For the examination of the rock mechanical behaviour, the water level in the well was lowered several times over a period of three years by a submersible centrifugal pump (and later with a sub-surface pump) and the subsequent recovery of the lowered water table was carefully recorded as a measure of the rate of convergence of the cavern. The change of water level is shown in Figures 3 and 4. Additionally, four Echolog surveys were carried out to determine the amount of available net capacity. At the same time the existence of tectonic stresses—especially in the transition zone "Haselgebirge"/Upper Permian Salt—was investigated since these might lead to inhomogeneous deformations of the cavern.

In conclusion it can be said that the measured convergence can be mainly attributed to the evaporites of the "Haselgebirge." The appearance of fracturing can be explained by a too rapid pressure release that led to a build up of stress too rapidly to be compensated by the plastic flow of the salt. In this way stresses were obtained exceeding the brittle strength. The maximum stress $p_o - p_i$ obtained was 313 kg/cm^2. A relatively narrow rock zone around the cavern was subjected for an extended time to an excessive stress difference and thus it contributed inordinately to the convergence. The interpretation led to an admissible minimum storage pressure of 80 to 60 kg/cm^2

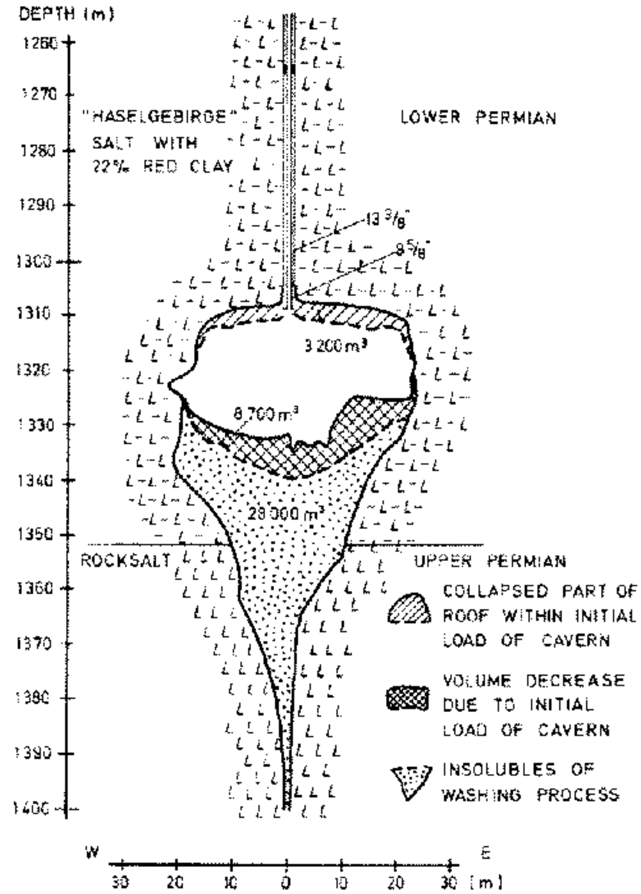

Figure 2. Cross Section of the Cavern Before and After Initial Load.

whereby a maximum gas withdrawal rate of 50,000 Nm^3/h is possible.

A first indication of the in situ strength of rock resulted by lowering of the water table which was performed after the completion of the storage well. After the lowering of the water table to 1,256 m (equivalent to a stress difference ($p_o - p_i$) of 312 kg/cm^2) symptoms of failure in the open hole, i.e., the future cavern area, could be observed.

From the rate of rise of the water table at equal depths (that is the slope of the curves in Fig. 5), a decrease in the rate of convergence is evident. The influence of time on the convergence rate is even more obvious from the water outflow data in Table I which have been obtained in a way similar to those available from the storage cavern Heide (Röhr, 1969).

TABLE I

Outflow Rate (dm^3/h)	Load Time (since end of leaching) (h)	Stress Difference (kg/cm^2)
45	350	164
16.1	12000	164
6.8	23000	164

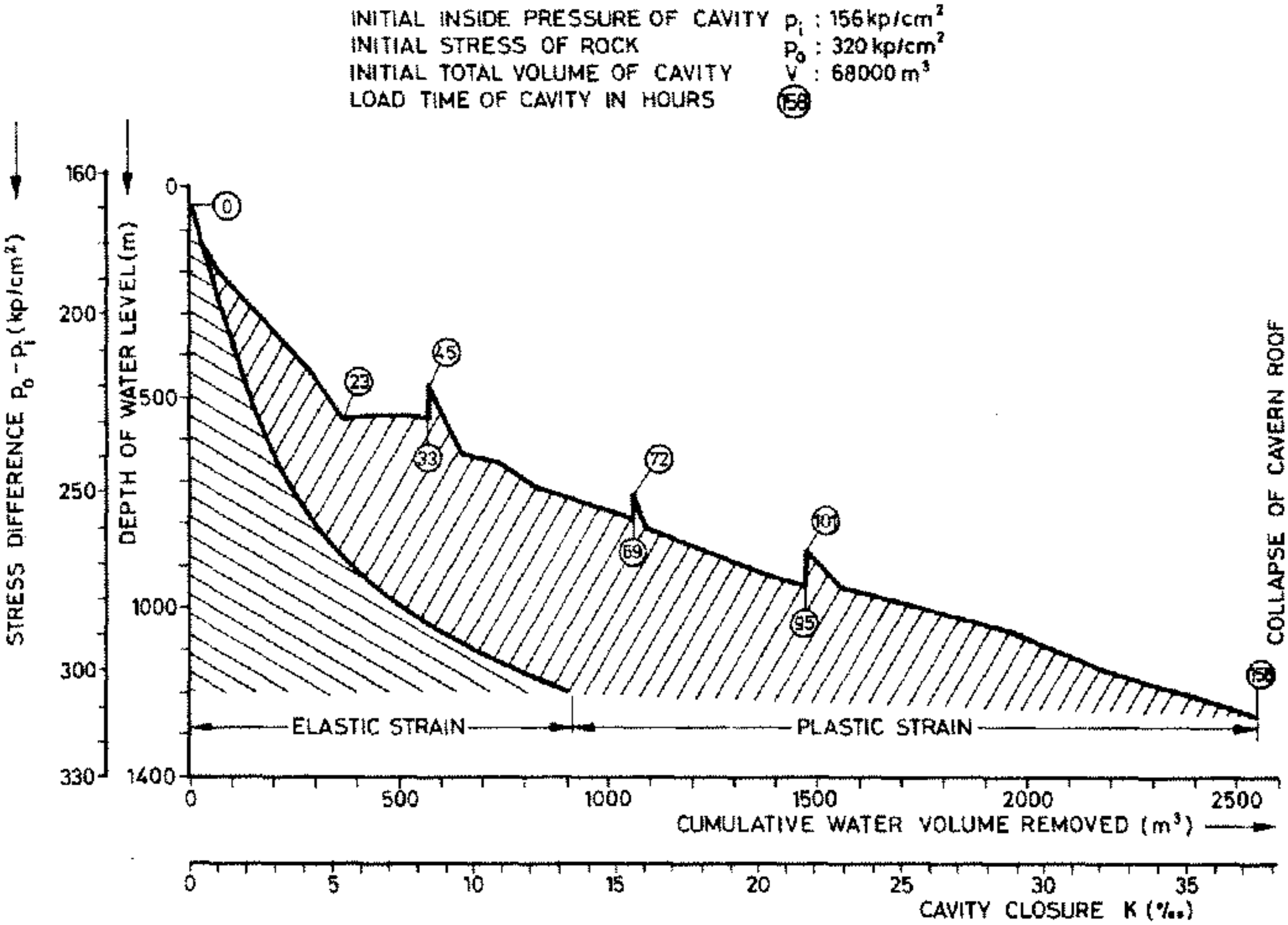

Figure 3. Initial Load of Cavern (kp = kg).

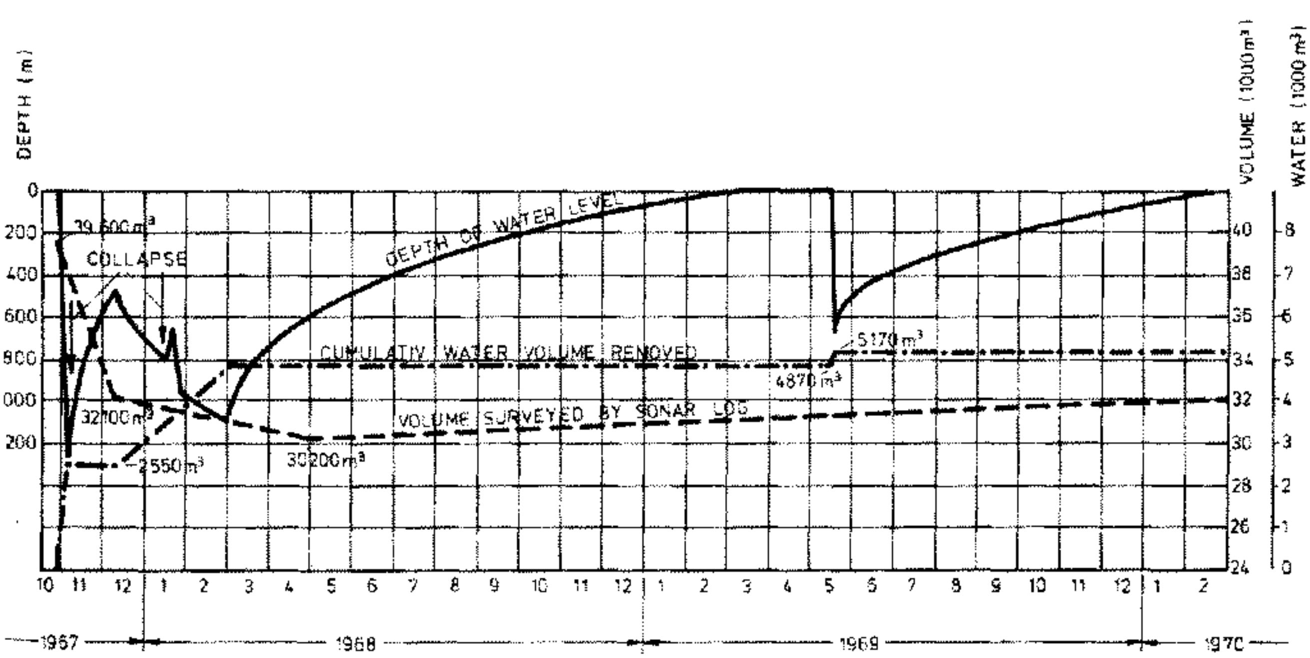

Figure 4. Changes of Volume Surveyed by Sonar Log Depending on Depth of Water Level and Pumped Brine.

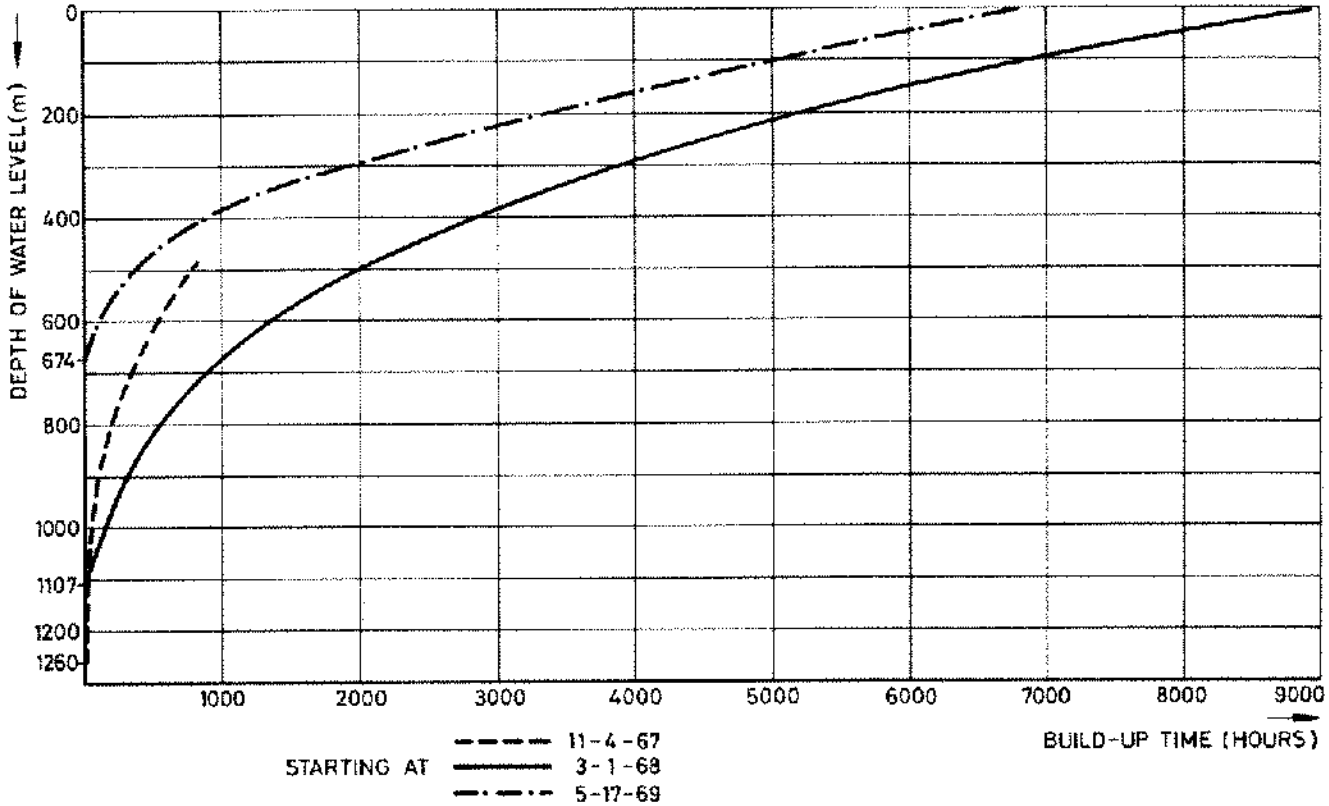

Figure 5. Level Increase Measurements.

In evaluating the outflow rate the influence of temperature must be taken into account. From the end of leaching the temperature in the cavern at a depth of 1,310 m rose within 282 days from 32°C to 46°C but was still well below the stationary wall rock temperature of 67.5°C. Within the observation time, the mean rate of temperature rise was 0.0495°C per day. This temperature rise corresponds to a mean outflow rate of 5.6 dm^3/h of water over the same period whereby the rate of temperature rise also decreases with time. The measured rates of outflow are many times greater than the quantities corresponding to the rate of temperature rise. These rates become negligible if the measurements of rise and fall of the water table are considered.

LABORATORY INVESTIGATIONS

The brittle strength of a standard cube from the "Haselgebirge" salt was measured on laboratory samples by Dreyer (1969). Table II shows the considerable decrease in the strength with increasing solid matter content.

On the basis of the brittle strength of a standard cube (302 kg/cm^2) found in the ceiling of the cavern, Dreyer (1967) compared the stability of the cavern to a model.

TABLE II

Solid Mater Content (%)	Brittle Strength of a Standard Cube (kg/cm^2)
0	380
20	305
40	265

From a sample with comparable rock mechanical properties a geometrically similar roof arch was modeled and placed under stress. Failure began at a stress difference (p_o–p_i) of 232 kg/cm^2. For this evaluation the most unfavourable value of a series of samples was selected. In the in situ tests on the cavern, failure started at a rate of stress of 0.054 kg/cm^2h and at a stress difference of 260 kg/cm^2. During the initial loading of the cavern fracturing occurred at a rate of stress of 9.6 kg/cm^2h and at a stress difference of 313 kg/cm^2. These values confirm the laboratory investigations that the values for brittle strength rise with an increased rate of stress. The lower rate of stress probably corresponds to a quasistatic stress and thus would yield the minimum brittle strength. Nair (1969) observed in a laboratory test that failure began at a stress difference (p_o–p_i) of 288 kg/cm^2 after 1310 minutes and a total deformation of 6.95%.

EVALUATION

The objective of the interpretation was to describe the different phenomena of fracture and flow by means of a mathematical model and thus predict the lifetime of the cavern under different operating conditions.

In an earlier paper by Röhr (1969) a method for determining in situ the modulus of elasticity of rocks around a spherical cavity was described. In the pressure tests of the Kiel storage cavern, the cavern pressure was reduced and the amount of water forced out was measured. The ratio of the amount of water dV to the drop in pressure dp_i is related to the modulus of elasticity E and the compressibility of brine C_K as shown in formula (1).

$$\frac{dV}{dp_i} = V\left(\frac{9}{4E} + C_k\right) \quad \left(m^3 \cdot cm^2/kg\right) \qquad (1)$$

The in situ modulus of elasticity at a stress difference of 164–110 kg/cm² was determined to 175–200,000 kg/cm².

The description of the plastic behaviour of rocks around a spherical cavity was based on formula (2) which has already been used in various other publications (Boresi and Deere, 1961; Dreyer, 1969; Kühne et al., 1973; Röhr, 1969; and Thompson and Rippenberger, 1964).

$$K = p \cdot \left(\frac{Po - Pi}{100}\right)^n \cdot \left(\frac{t_h}{1000}\right)^m \ (\%) \qquad (2)$$

The meaning of the symbols is listed in Table IV.

The constants p, n, m in the various publications were determined from laboratory tests and differed considerably. Besides this the temperature and the general state of the rocks are of importance. According to formula (2) salt begins to flow at the smallest stress difference. However, if one supposes that a definite yield stress σ_o exists for salt, flow starts only if the actual stress difference $(p_o - p_i)$ exceeds this yield stress. In this case a cavity in salt would not close completely. Röhr (1969) has already discussed which asymptotic values of the convergence are to be expected for different yield stresses. In the storage cavern Heide 101 a yield stress of 26.4 kg/cm² and a modulus of elasticity of 200,000 kg/cm² was found in situ. The in situ yield stress for the rock of the Kiel 101 storage cavern was taken from the asymptotic water table in long term measurements of the water table.

The rise of the water table is identical with the rise in pressure. The yield stress σ_o is calculated from formula (3) for E = 200,000 kg/cm².

$$\sigma_o = \frac{1.5\ (Po - Pi_\infty)}{1 + \ln\left(\frac{E \cdot C_k}{2.25}\right)} \ (kg/cm^2) \qquad (3)$$

Herein $p_{i\infty}$ is the extrapolated asymptotic value of the inside pressure. Figure 6 shows a semilogarithmic representation of the water table measurement data that leads to the asymptotic value $p_{i\infty} = 222$ kg/cm².

Table (III) shows the asymptotic cavity convergence to be expected for a yield stress $\sigma_o = 83$ kg/cm².

TABLE III

Cavity Convergence Vol. %	Stress Difference $P_o - P_i$ (kg/cm²)	Modulus of Elasticity (E) (kg/cm²)
0.36	150	190,000
1.22	200	135,000
5.4	240	60,000
9.3	250	40,000
17.5	260	20,000
32.2	265	10,200
100.0	270	0

The fact that the yield stress in the Kiel cavern is higher than in the Heide cavern could be explained by a hardening of the salt following intensive deformation. On the other hand the sediment content in Kiel (average 22% by volume) was higher than in Heide (9% by volume).

For the recalculation of the various water table rise and fall values, formulas (1) and (2) were combined into the differential equation (4) which was solved by means of a computer program.

$$\frac{dH}{dt_h} = \left(\frac{dH}{dV}\right)_{el} \cdot \left(R - c\left[\frac{P_{io}}{100} + \frac{\gamma_{sol} \cdot H}{1000}\right]^n \cdot t_h^{\ m-1}\right) (m/h) \qquad (4)$$

Herein $\left(\frac{dH}{dV}\right)$ el is the reciprocal value of the elastic deformation of the cavity caused by the change in water table according to formula (1).

TABLE IV

Nm^3/h		meters cubed/hours under standard conditions, i.e., 0°C and 1.013 bars
C_K	$(kg/cm^2)^{-1}$	compressibility of brine
E	(kg/cm²)	Young's modulus
H	(m)	decrease of level measured from the surface
K	(%)	closure of cavity volume
P_i	(kg/cm²)	inside pressure of the cavern
P_o	(kg/cm²)	initial stress of rock
P_{io}	(kg/cm²)	difference $p_o - p_i$ at a brine level equivalent to a surface level, in this case 164
R	(m³/h)	pumping rate
t_h	(h)	load time
V	(m³)	total volume of cavity
a_{sol}	(kg/dm³)	specific gravity of brine
σ_o	(kg/cm²)	yield stress

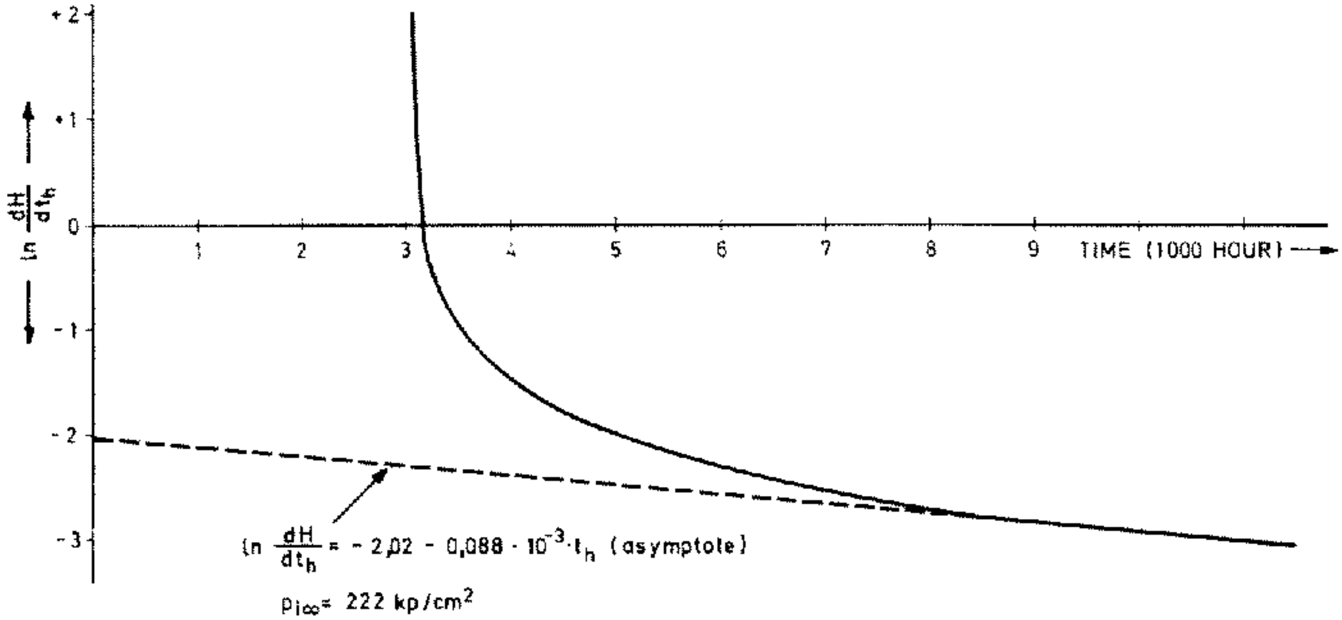

Figure 6. Velocity of Level Decrease; Diagram to Find the Asymptotic Inside Pressure of the Cavern (kp = kg).

The purpose of the recalculation was to determine the unknown constants p, c, n, and m in such a way that the observed levels could be recalculated optimally. This recalculation showed that the modulus of elasticity decreased to zero with increasing stress difference. It was thus possible to estimate the brittle strength from the modulus of elasticity. Figure 7 shows that at a stress difference of 270 kg/cm^2 Young's modulus becomes zero and that value can be assumed as the brittle strength. From the least favorable value of each series, Dreyer obtained for laboratory samples the brittle strength as 232 kp/cm^2.

In laboratory tests on "Werra" rock salt F. Schuppe (1963) proved that with increasing stress difference the modulus of elasticity decreased from a maximum to zero (Fig. 7). Again the stress difference for $E = 0$ is the brittle strength. In the in-situ investigations (Fig. 3) the decrease of the modulus of elasticity is reflected in the fact that after interruptions of pumping increased amounts of water had to be pumped with increased stress difference if an equal decline of the water level was to be maintained.

Furthermore the curves of water level decline after interruption of production show an abrupt change of slope which separates the range of predominantly elastic behaviour from that of elasto-plastic behaviour. A similar fact was observed in laboratory tests and was described by Dreyer (1967) as the maximum curvature method for the determination of in situ rock stress. The experimental values used together with the differential equation (4) for the calculations varied widely: the time t_h between a few and 18,000 hours, the pumping rate R between 0 and 19 m^3/h, and the differential pressure (p_o–p_i) between 164

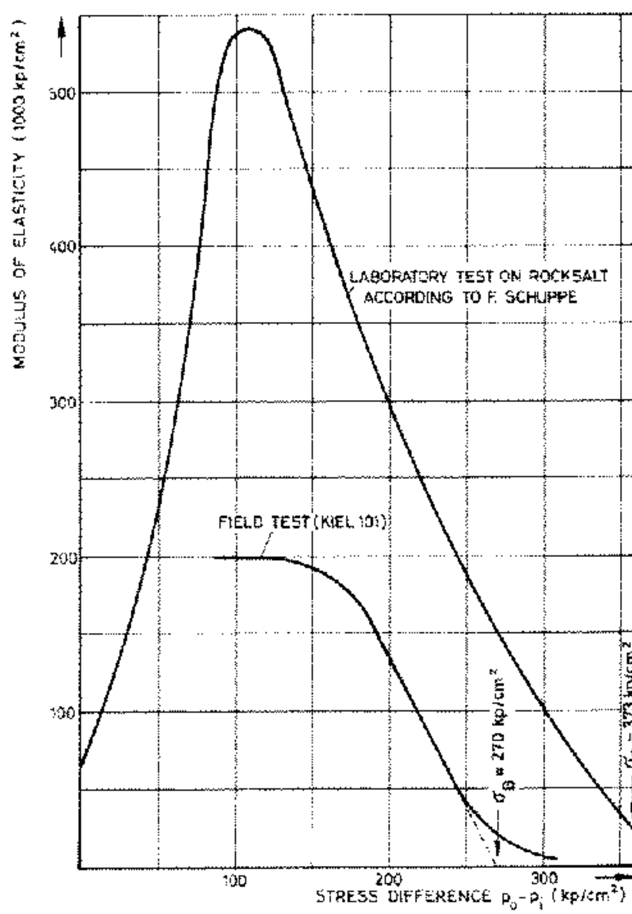

Figure 7. Elasticity Modulus; From Laboratory Test Schuppe (1967); From Field Test (kp = kg).

and 310 kg/cm². The load time is meant to be the time during which the stresses were active.

Table V shows the limits between which the values c, p, n, and m must lie for Kiel 101 to guarantee an optimal agreement between calculation and observation.

TABLE V

	Boundary value Kiel 101		According to Dreyer (1969)	According to A.P. Boresi and D.U. Deere (1961)
p	$1{,}106.10^{-4}$	$1{,}116.10^{-4}$	$6{,}308.10^{-2}$	0.37
n	10.5	8.0	1.2	2.65
m	0.43	0.39	0.94	0.3
c	0.00166	0.02	—	—

It is remarkable that the time exponent m fluctuates so little. The stress exponent n between 8.0 to 10.5 is considerably higher than the values resulting from laboratory measurements published by Dreyer (1969), Boresi and Deere (1961). Figure 8 shows a graph of the convergence values corresponding to Table V.

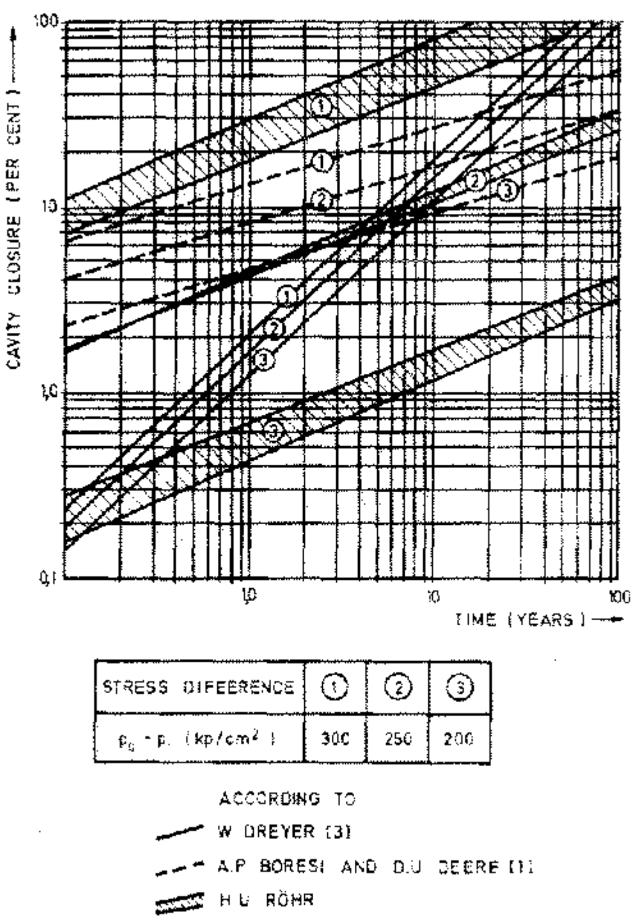

Figure 8. Creep Closure of a Spherical Cavern.

The order of magnitude of the measured convergence is indicated by the following figures: In connection with the water table decline 5,100 m³ of the water were cumulatively extracted from the storage cavern that can be traced back to the convergence. Parallel to this the cavern volume obtained from echometric measurements decreased from 39,600 m³ to 32,000 m³. This last figure was corroborated by the fact that only 32,000 m³ of brine could be forced out by the initial filling of the cavern with town gas.

If the water production rate of 5,100 m³ is considered with regard to the initial cavity volume of 68,000 m³ the convergence of volume during testing time was 7.5%. After a further volume convergence of 47% the useable volume becomes zero. The lifetime of the cavern at various stress differences (p_o–p_i) can be taken from Fig. 8 as the time when the volume convergence is 47%.

CONCLUSIONS

The tests and evaluations described in this paper made possible the prediction of the lifetime of the cavern in dependence of the inside pressure p_i. The stress p_o in the virgin rock can be assumed to be 320 kg/cm². To guarantee a lifetime as long as possible the storage cavern at present is operated at a mean inside pressure of more than 100 kg/cm².

The maximum storage pressure depends on the design of the storage well and amounts to 160 kg/cm². A pressure of 60 kg/cm² was accepted as the minimum storage pressure.

In the vicinity of this pressure value the beginning of fracturing is to be expected. The planned 50,000 Nm³/h are admissible as a maximum extraction rate from the cavern. This extraction rate corresponds to a loading rate of 1.1 at/h equivalent to 81 kg/cm² within 72 hours which could be achieved without fracturing.

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