Long-term Operation of Underground Storage in Salt

A. Clerc-Renaud and D. Dubois
Geostock, Tour Aurore, Cedex 5, F 92080 Paris, France

ABSTRACT

More and more countries are building underground storage caverns in salt for oil products. The caverns are deeper because the shallower locations have already been used. The greater the depth, the greater the problem of long term operation because stability of the cavern becomes a major component of economic and environmental planning. Stability depends on the rheological behavior of salt. Some models can be found in the literature, but large discrepancies can result when one uses one or another of them. Geostock, which operates 34 caverns at Monosque, France made in situ measurements in its caverns in order to select from the available models the one which best represents their behavior. The paper describes these in situ operations after 8 years of operation, the type of rheological model and the results which can be expected with extrapolation for a long period.

INTRODUCTION

The problem of the lifetime of storage cavities in salt becomes more and more critical as 1) the cavities which were built at first are now relatively old (10 years and more in France), 2) the new ones are leached to greater and greater depths, because the shallow locations have been used, and, 3) people and authorities are more and more interested in environmental consequences of industrial activities. We are now asked in France to look at how the underground facilities will affect the world which coming generations will inherit from us.

When we began building Manosque (France), we entered into the problem through what had previously been published, but we were stopped by the diversity of the theoretical proposals we found in the literature for formulating salt and cavity behavior. This was only 10 years ago.

Laboratory measurements themselves exhibit a large scatter in the data. This results in many discussions about what the material is, how measurements are made (devices, type of sampling, and so on) and, what is more serious, the representativeness of some of these measurements. That is the reason why at the beginning, we were perplexed when we had to establish a basis for determining the size and method of operation of our caverns.

As we operated the cavities ourselves, we decided at once, to perform in-situ observations in the first ones. As far as we can know, such a full set of observations has not been yet made on any set of 34 caverns together. The publication of these results seems to us to be useful.

The following information concerns mainly the operators of such storage cavities, but they were collected to answer the problems of our rock mechanics engineers.

THE SALT IN MANOSQUE

The salt is of Oligocene age. It was deposited in a continental basin with a large subsidence, resulting in thick deposits (Apt-Forcalquier Basin). The Alpine orogenesis, at the end of Miocène, later gave the area its present architecture. The salt lies in an east-west anticline. Tectonic thrusts have deformed the evaporite layers, forcing the salt into greater thicknesses, varying according to the location in the anticline. The layers of insoluble materials, mainly anhydrite, were broken into small pieces of generally decimeter size. In such a configuration, the salt appears almost as a diapir, though it has never thrust through the overburden in any place. The average proportion of insoluble materials is 12%.

Laboratory behavior of the manosque salt. The Mohr diagram of a series of triaxial tests appears classic (Fig. 1). The envelope of the Mohr circles may be represented with a Coulomb's line in the region of small and medium stresses, and with a Tresca line for larger stresses.

BEHAVIOR OF THE CAVITIES

The volume of these cavities ranges from 100 to 500,000 cubic meters. The height of the excavations is in the range from 150 to 400 meters. The lowest points of individual cavities vary from 400 to 1,600 meters below the ground surface. The maximum diameters are 70 to 80 meters. We performed in-situ measurements, including thermal behavior, response to depressurization, response to pressurization, and response to alternating pressurization/depressurization.

Thermal behavior. The brine in the cavity, at the end of solution mining, is colder than the undisturbed rock around it (40° to 50°C) because the fresh water is cold (5° to 15°C) and because the solution process is slightly endothermic. The pumping of oil into the cavity does not modify the internal temperature much. There is then a period in which the fluids inside, the walls, and the insoluble materials which fell to the bottom slowly warm up.

If the well head is kept shut in, the confined thermal expansion results in a growing pressure. (Fig. 2)

The results showed that during a small interval of time, say one week, the pressure rises proportionally with time (line A). However this can be observed only if the starting situation, at 0, is a stabilized one. If the cavity has just been depressurized, we find curve B. If the cavity has just been pressurized, we find curve C.

The reason for the differences is in viscous effects becoming measurable with significant pressure variations. For the same reason, if the shut-in period is long enough, it may be possible to observe the curve A', as viscous effects become significative. The value of α is the amount of pressure which should be bled off (psi/day) in order to keep a constant pressure at the well head.

This value can be written in terms of m^3/day, as long as the pressure variations are in a range small enough to assume elastic behavior.

In practice, we bleed the pressure off regularly in order to keep it at a near constant value; but it is possible to repeat the observations at later times. The angle α decreases with time. The whole of the α values vary about proportionally to log time, in the first years at least (Fig. 3). During this time, the temperature continues rising in the cavity. One can compute that the thermal volumetric expansion of the

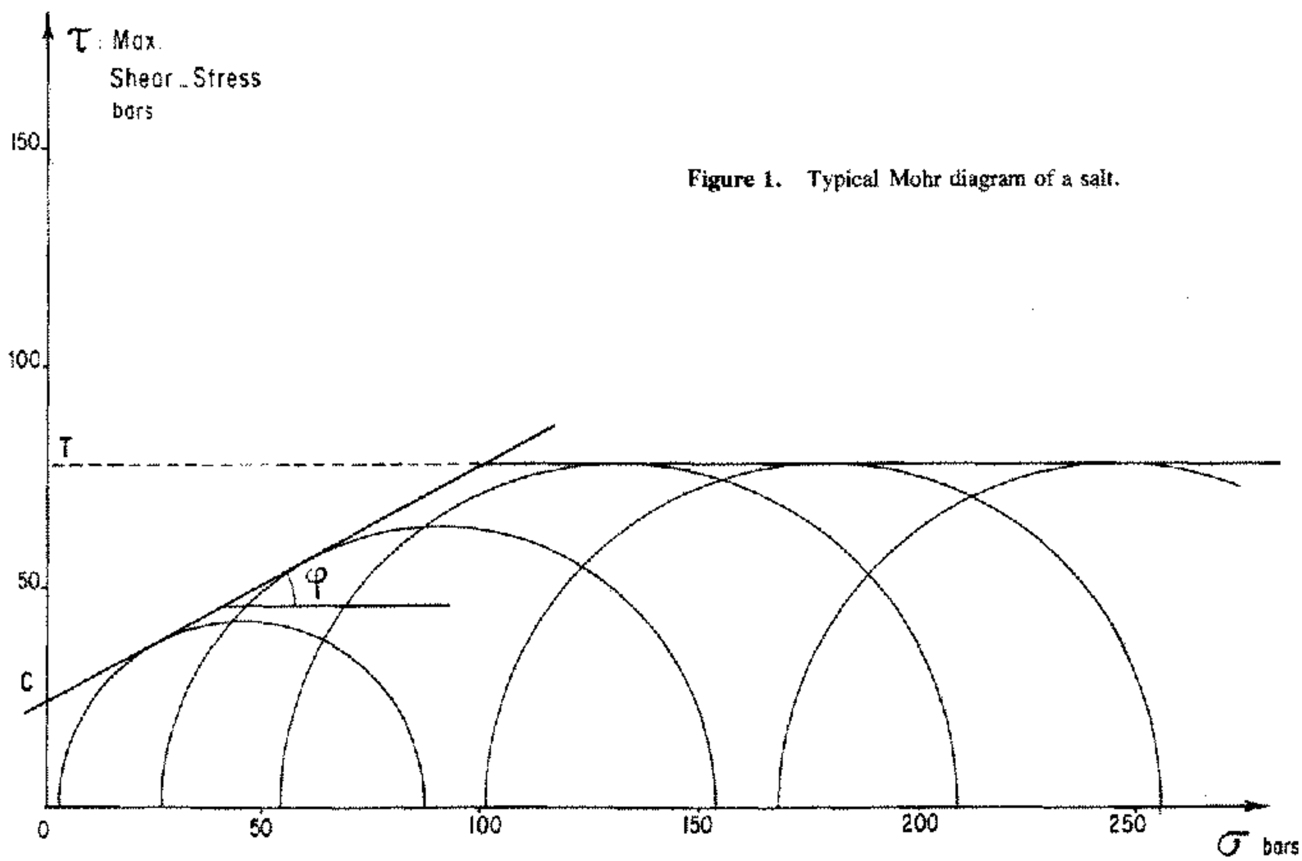

Figure 1. Typical Mohr diagram of a salt.

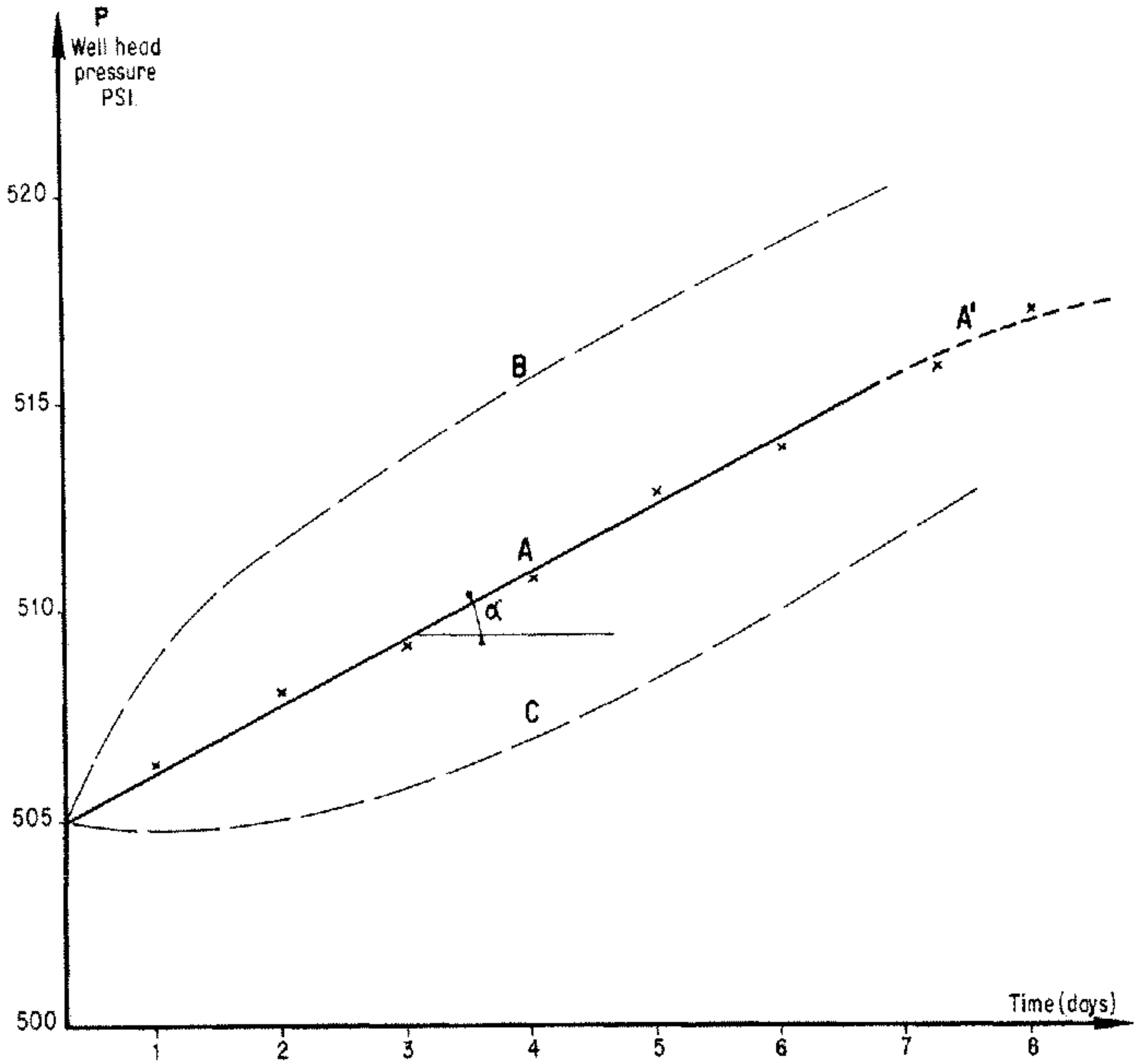

Figure 2. Thermal expansion of a closed cavity.

walls and insoluble materials at the bottom is of second order of magnitude, compared to the volumetric thermal expansion of the fluids (brine and oil). For several observations (Fig. 3), we also measured at the same time the temperature rise in the cavity. We found, for the observed cavities whose bottom was around 1000 m, that the volume of fluids which should have been removed from the cavity in order to keep a constant pressure at the well head, was practically equal to the volume of the thermal expansion of the fluids during the same period.

In this way, we were able to conclude that for such caverns where the bottom is around 1000 m, the roof is around 600 m, and the volume is around 250 000 m³), there was no significant volume variation from creep in the first years of operation. The accuracy of the measures was 200 to 300 m³ per year.

We were able to reproduce these observations with computer calculation. We found that for such caverns, thermal stabilization could be reached in practice only after about 10 to 12 years after the end of mining.

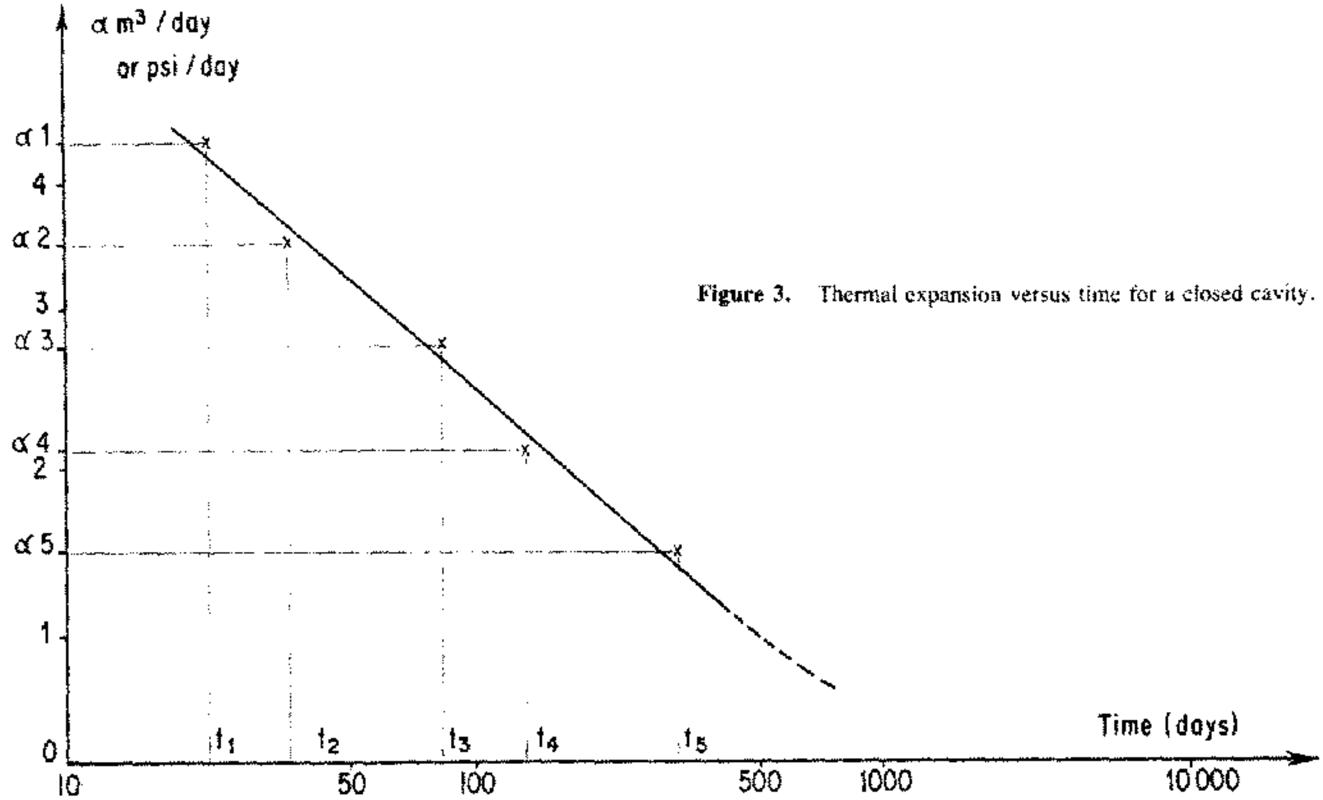

Figure 3. Thermal expansion versus time for a closed cavity.

RESPONSE TO PRESSURIZATION

We observed that during a rapid pressurization (1 to 2 hours), with small variations of pressure, (a few bars), the ratio $\Delta P/\Delta V$ remains constant. In fact, viscous effects begin, but for small variations of pressure, they cannot be detected with a standard dead weight tester with a sensibility 0.1 psi. This observation is in agreement with the thermal observations. This $\Delta P/\Delta V$ ratio is a kind of compressibility factor in an elastic situation. It is a complex one, as it includes the excavation, and the fluids, though, it is possible to compute a compressibility factor for the excavation alone, and from it to derive a value of the elastic modulus E, according to the shape of the cavity.

For instance: $C = 2 \dfrac{1 + \gamma}{E}$ for a cylinder.

We were surprised to observe that in each case, E values ranged from 240,000 to 340,000 bars, instead of 30 to 50,000 initially measured on cores in labs.

Of course, the in-situ value is used in finite element models.

RESPONSE TO DEPRESSURIZATION

Known parameters include the geometry of the tubes in the cavern inside tubing with brine, and oil in the annulus. As the brine has a greater specific gravity, there is excess pressure on the annulus. The following tests were performed.

1. Starting from the normal operating situation (overpressure in the annulus), oil is removed in order to decrease the well head pressure. The base of the cavities is always at 1,000 meters. At the beginning, the decrease of the well head pressure is proportional to the volume of oil removed (Fig. 4). After the point b, the decrease is slower. Point b is the beginning of the creep. In fact, the position of point b depends on the rate of oil removal and the depth of the cavity. There are some mathematical models in which the pressure of point b is expressed in terms of the parameters C and ϑ (Coulomb's line), and depth.

With several cavities at different depths, it is possible to compute C and ϑ in-situ values. It is then possible to predict the position of the point b for future cavities at other depths, under the same conditions of depressurization. In Manosque we found C and ϑ in-situ values not too far from the measured values in laboratory tests.

2. When the cavity is completely depressurized, with atmospheric pressure on the annulus, oil continues flowing, at a decreasing rate.

Figure 5 represents on the left side the standard evolution of the increase of the well head pressure with time corresponding to thermal expansion. At time P, the well head pressure was lowered to atmospheric pressure as indicated before. Then, with constant atmospheric pressure, the volume of oil flowing was measured every day ($\overline{ca}$).

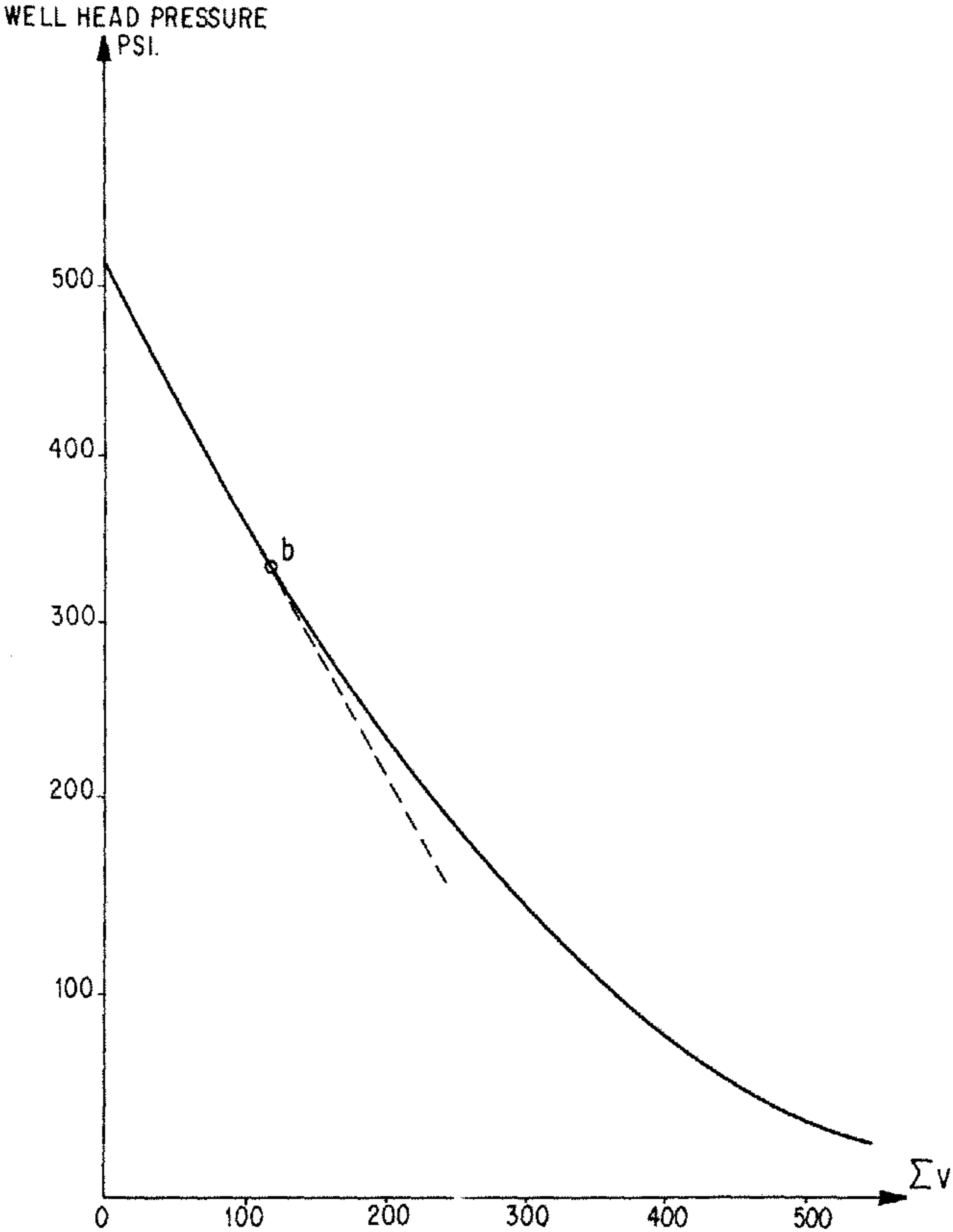

Figure 4. Depressurization of a cavity. Well head pressure versus cumulative withdrawal volume.

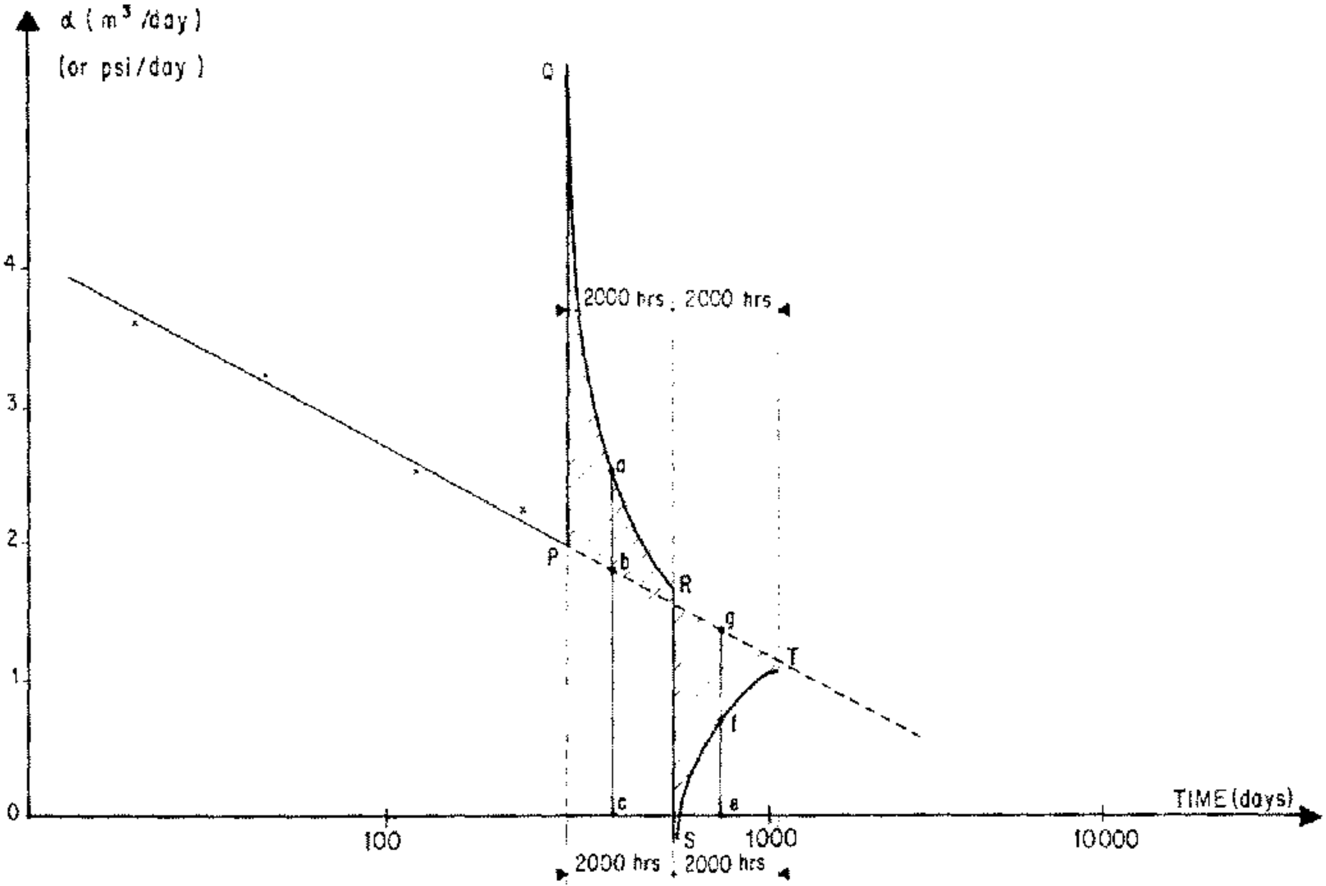

Figure 5. Response to a 2,000 hour depressurization. Well head oil pressure before P = 550 psi; between P and Q = atmospheric, and after Q = 550 psi.

The total flow $\overline{ca}$ in a day has two components, $\overline{cb}$ corresponding to the normal thermal volumetric expansion, from the preceding measurements and, $\overline{ba}$ is an extra flow, which can be considered as creep for the moment. In this experiment, the duration of the period QR was 2,000 hours.

At time R, oil was again pumped into the cavity (in one day) in order to reestablish the former values of pressure on both sides of the well head, (the same values as in P), and daily observation of pressure started for a new period of 2,000 hours. The actual increase of pressure, ef, results from the normal thermal expansion (eg), *less* the "creep" component fg.

This experiment resulted in two conclusions for the behavior of the cavity

1. In a depressurized situation, the daily expansion tends towards the normal thermal expansion. After repressurization, the evolution of the daily expansion is similar, but less than the thermal expansion.
2. The areas of the PQR and RST are either the cumulative extra flow or the cumulative deficit of pressure, i.e. an extra outward flow which would have been necessary to keep the daily pressure at the level of the thermal expansion, or the inward flow that would be required to keep the pressure at this level. Both areas were found to be practically equal. That means that the wall movements during both periods were practically symmetrical and that the phenomenon is a reversible one. It is a viscous effect, in rock mechanics terminology, and not plasticity.

RHEOLOGICAL MODEL

Further, the value of $\overline{eab}$ (Fig. 6) was computed. That is the cumulative extra flow during the first period, and we adjusted a rheological model to fit this curve. Starting from a generalized model of the Maxweel type (Fig. 7), we found that we could represent this phenomenon with this type of model, with:

$G_1 = 5.31\ 10^4$ bars
$G_2 = 4\ 10^4$ bars
$G_3 = 4.38\ 10^4$ bars
$7_2 = 2\ 10^5$ bars × day
$7_3 = 1.9\ 10^6$ bars × day

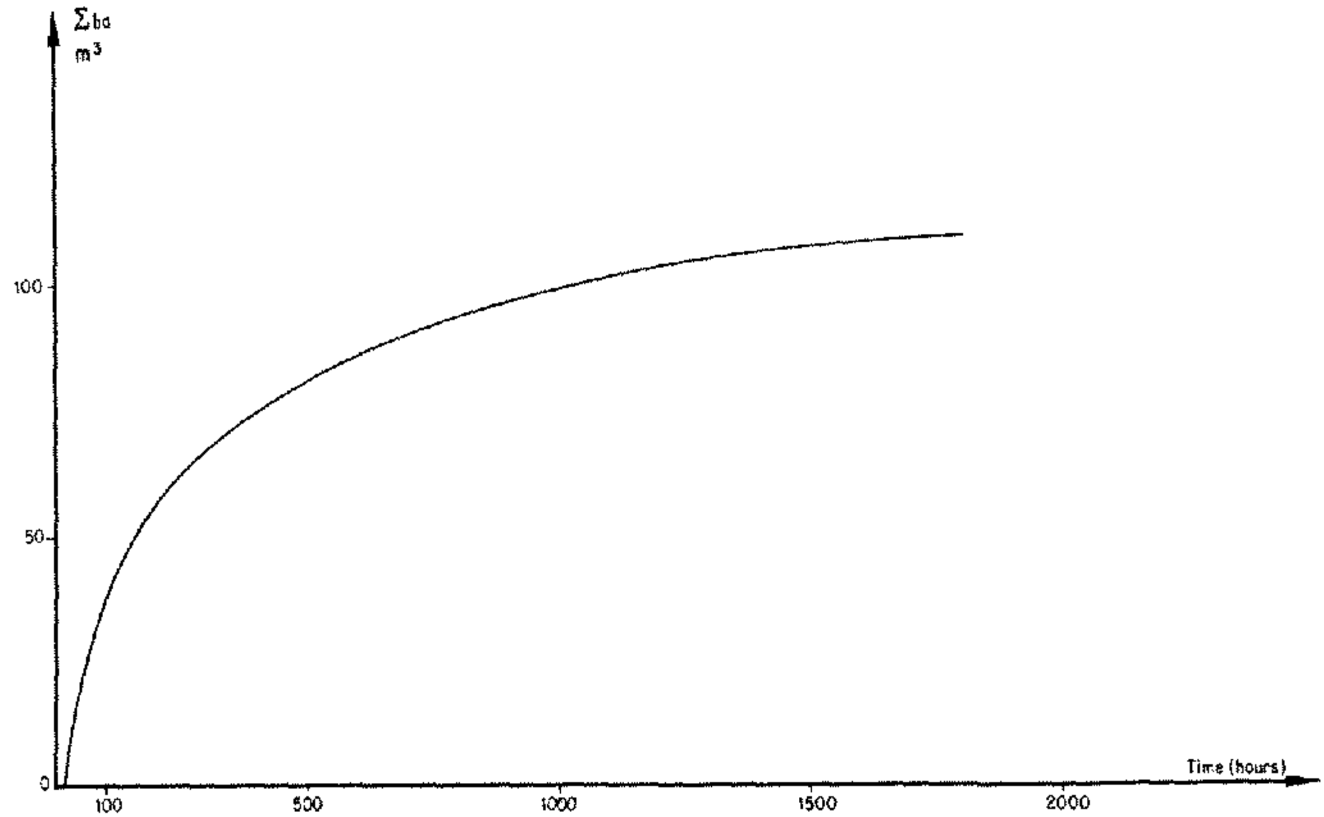

Figure 6. Response to a 2,000 hour depressurization cumulative extra-expansion (recoverable creep).

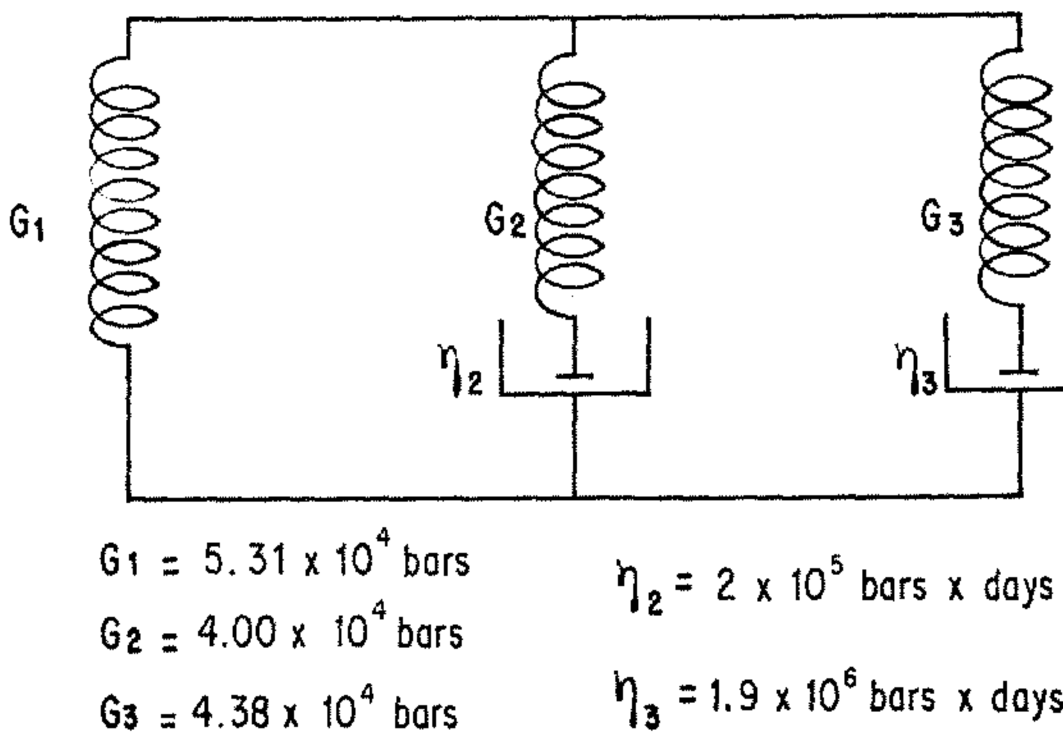

Figure 7. Fitting of a model of the generalized Maxweel type with the results of the 2,000 hour depressurization test.

The model was completed with plasticity parameters derived from lab experiments, because plasticity was never observed in-situ.

We extrapolated these results, established at 1,000 meters, to depths down to 1,600 m. Later, when we had leached cavities at this depth, we could verify the accuracy of the model for our salt and did not observe any significant plasticity effects in these caverns full of brine. The model does indicate, however, that there are some plastic zones beginning along the vertical walls.

The model allows more precise conclusions than in-situ measurements, because in the preceding test, we had to stop it after 2,000 hours, when the errors in measurement were in the same range as the measured quantities. With the model, we found that the stabilization of the movement, for a given inside pressure, is obtained after about 120 days at 1,000 m, 150 to 200 days at 1,600 m.

SIZING OF THE CAVITIES

With this model, it is possible to predict the mechanical and volumetric behavior of a cavity alone, of a line of cavities, or also of a system of several parallel lines, but it is not sufficient for the complete design of a system of cavities. The sizing of cavities depends also on the safety coefficient desired, with respect to the long term strength.

This involves the human judgement on the questions of: what degree of safety is necessary? what is the theoretical long term strength of the salt, where we can only know the "instantaneous" strength?

We have our own policy on these questions, and it would be too long to develop it here.

LONG TERM OPERATION

We verified that the first cavities leached were volumetrically stable; of course, some delayed variations of volume related to the variations of pressures are observed, but they are reversible ones in the cavities of Manosque, at 1,000 m or shallower when filled with brine or oil. This is a viscous effect, not a plastic one. This effect has a limit.

The same applies in cavities at 1,600 m, with the exception that plasticity begins at this depth. However plastic effects are too small to be measured in field conditions.

After 9 years of operation of the first 18 cavities, we began to observe and measure another phenomenon, the volume of the insoluble material at the bottom increases abnormally. From the mining data, we know the relationship between the volume of these insoluble materials at the bottom and the volume of the dissolved salt. To move the oil, we displace it with brine. This brine is not completely saturated, and there is some small enlargement of the cavity. The volume of insoluble materials produced by this enlargement is greater than the one computed from the mining data.

Figure 8 shows that for most of the cavities, the observa-

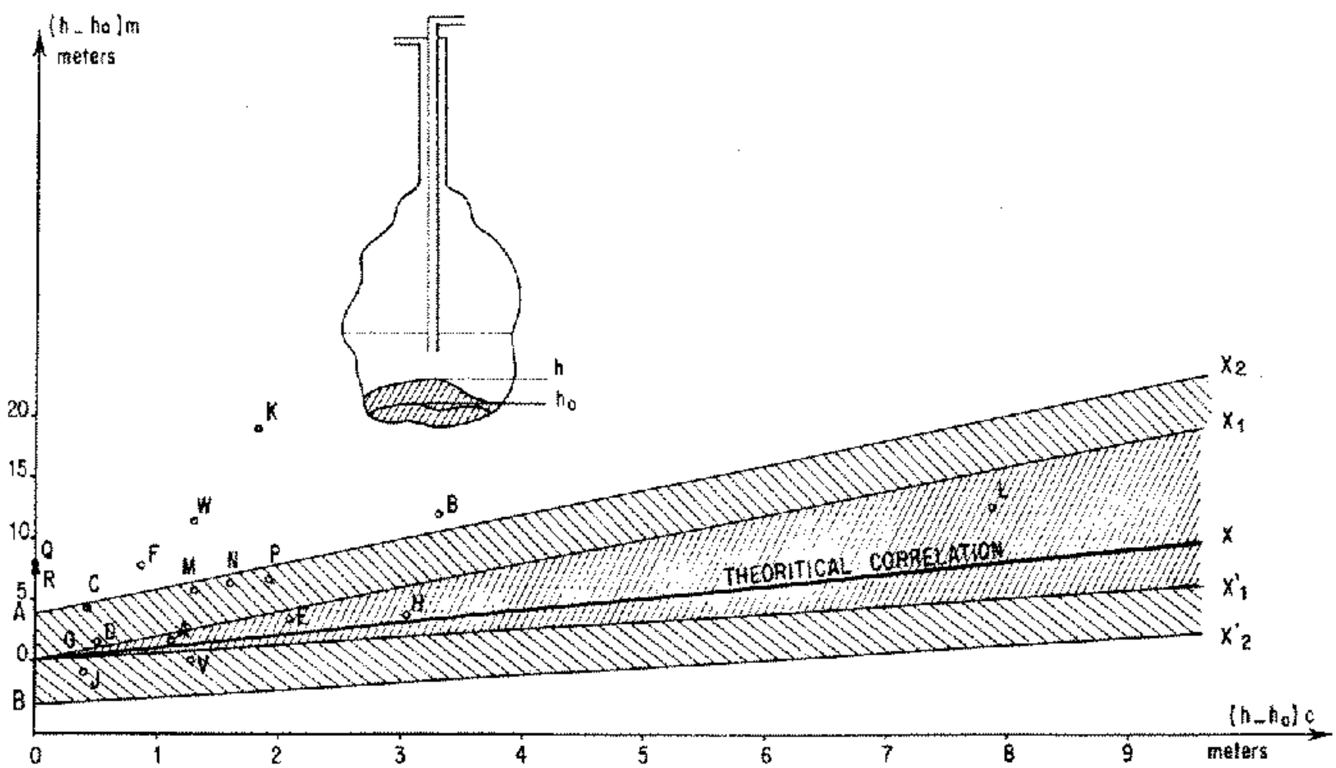

Figure 8. Correlation in Manosque between $(h\_h_o)m$ and $(h\_h_o)c$, where h_o = depth of the bottom when filling with oil for the first time, h = actual depth; $(h\_h_o)m$ = measured difference and $(h\_h_o)c$ = computed difference.

tions remain close to the estimated errors of the measurements. But, 16 cavities among 18 are on the same side of the perfect correlation and we are sure that two of them really have rising bottoms, as the error cannot reach the observed values.

As we have no other volume variation than thermal expansion, we conclude that blocks fall on the bottom. The reason is spalling.

Of course, it is not possible to have creep exclusively at the bottom. Moreover all stress calculations show that the most stressed parts of the walls (for a same safety coefficient) are the vertical walls at some distance above the bottom. The reason for spalling is the heterogeneity of the walls in shape and the irregular pattern of the insolubles. Small pressure variations are sufficient to initiate spalling (e.g., oil movements, periodically bleed off of the well head pressure because of the thermal expansion). No rheological model is able to predict spalling under such conditions.

So, although we verified that these cavities were *volumetrically* stable, their mechanical stability is not infinite. If operation should continue under present conditions, one can predict that the lifetime of such cavities might be no greater than some thousand years. After this period of time, they would be completely filled, as the volume of falling rock occupies more space than originally, part of the cavern volume becoming transformed into small voids which are not available for storage. Since we know that the expansion coefficient for the bulk volume of the falling blocks is in the range of 1,8 to 2; then, the falling blocks at the bottom will reach the roof when excavation is doubled, approximately. In the usual range of the depths of cavities, this does not represent too great damage to surface ecology for our heirs.

GENERAL CONCLUSIONS

In these storage cavities, in pure halite with some insoluble materials, the bottoms of which are no deeper than 1,600 meters, we observe that.

1. There are only small and temporary movements of the walls.
2. The movements are of limited expansion.
3. They are in both directions, towards the inside or towards the outside according to the sign of pressure variation.
4. They are of limited duration (around 150 to 200 days at 1,600 m).
5. The bottom of the cavities rises slowly. The reason for this is spalling along the walls.
6. We are of the opinion that in such cavities it is spalling that will limit their lifetime, rather than steady creep, as it is too often assumed for the same conditions.
7. The lifetime of these cavities presently can be estimated to be in the range of one thousand years based on observations since 1969.