Long Term Creep Closure of Solution Cavity System

Robert Chao
Serata Geomechanics
Berkeley, California

ABSTRACT

When multiple cavities are created in a salt formation, they experience much greater creep closure in both magnitude and duration than predicted by the conventional finite-element computational method. This phenomenon occurs regardless of cavity usage. In order to analyze this long-term large creep deformation, a special numerical technique employing a computer simulation method was developed in our laboratory. This technique introduces the concept of "deterioration function" of material properties in which the property coefficients change with time rather than remaining fixed constants. The deterioration functions are determined from comparison of conventional finite element solutions with in situ stress-strain observations under controlled boundary conditions made by Dr. Serata using his instruments in various salt and potash mines over the past 10 years. The results of such studies indicate that when there are two or more cavities in the system, they produce a strong creep interference with each other even at large separation distances. The closure continues over many decades even after stress equilibrium of the system has been established. This creep interference is further intensified by an increase in the number of cavities in the system.

INTRODUCTION

Up until the present time, there has been no effective method of predicting solution cavity behavior. There exists a large discrepancy between conventional theoretical solutions including that by the finite element method and actual field observations. The difference is significant particularly when:

1. multiple cavities are created in a salt formation;
2. duration of creep is long lasting;
3. magnitude of creep is large;
4. material properties change with time;
5. cavity pressure fluctuates over a wide range.

These are fundamental rock mechanics problems which must be solved if cavity closure is to be minimized. The problems are serious regardless of cavity usage, whether it is for liquid or gas storage or even for solid waste disposal. These problems create the need for developing a technique useful for predicting the long-term behavior of multiple solution cavity systems.

This paper presents such a technique which was developed in our laboratory under a coordinated study of laboratory testing and underground observation. The technique is called the "deterioration technique." It is a computer method which first identifies the real difference between theoretical solutions using material coefficients determined in the laboratory and long-term field measurements. Then this difference is expressed as an empirical function of deterioration in which the material properties change or deteriorate with time. By introducing this deterioration function back to our theoretical method, the computer solution is matched with real cavity behavior. Thus the technique consists of two parts, theoretical and empirical. It is a hybrid model created by combining the plasticity theory, finite element method, long-term laboratory and field measurements. This technique was found to be in good agreement with field and laboratory observations made over the last several years. By utilizing such a technique, we can quite accurately predict the behavior of salt cavities over a long period of time, up to several decades. We are also able to evaluate the effects of basic design parameters upon cavity closure and stress distribution on existing cavities.

With careful consideration of specific field conditions, the technique can be utilized to produce optimum design and operational criteria. Basic parameters such as depth, material properties, cavity pressure, cavity shape, cavity separation distances, number of cavities and temperature can all be evaluated in regard to their effects on long-term creep deformation of the cavities. The evaluation of the parameter effects can be made individually as well as collectively. A specific set of these basic parameters is incorporated into the computer simulation each time. Important aspects of their effects on cavity closure are presented in the following sections.

CAVITY CLOSURE

The amount of cavity closure is a highly nonlinear time-dependent function of several factors. The most significant ones which will be examined here are: deterioration of material properties, differential pressure, separation distance between adjacent cavities, and the number of cavities in a system. Each of these factors can have a significant effect on the amount of cavity closure at any given age of a cavity or cavities.

DETERIORATION FUNCTION

The effect of deterioration function, ξ, on cavity volume reduction is shown in Figure 1. This function describes the basic material behavior which is due to the granular composition of rock salt. Under a given set of conditions, a cavity may have a varying amount of volume reduction depending on the material deterioration of the ground medium in which it is created. It is therefore important to check the deterioration function of the ground and take this factor into design consideration. In this particular example, if ξ is of the order of 1.4% to 1.7%, the volume reduction is less than 10% at $t = 100\ t_o$. If ξ is greater than 2.5%, considerably more volume reduction results in a short time.

The stress distribution pattern around a cavity is highly dependent on the rate of deterioration, as illustrated in Figure 2. The extent of the plastic zone, which affects creep in a nonlinear way, is itself a nonlinear function of the deterioration rate. The peak of the curves, which indicates the extent of the plastic zone away from the cavity

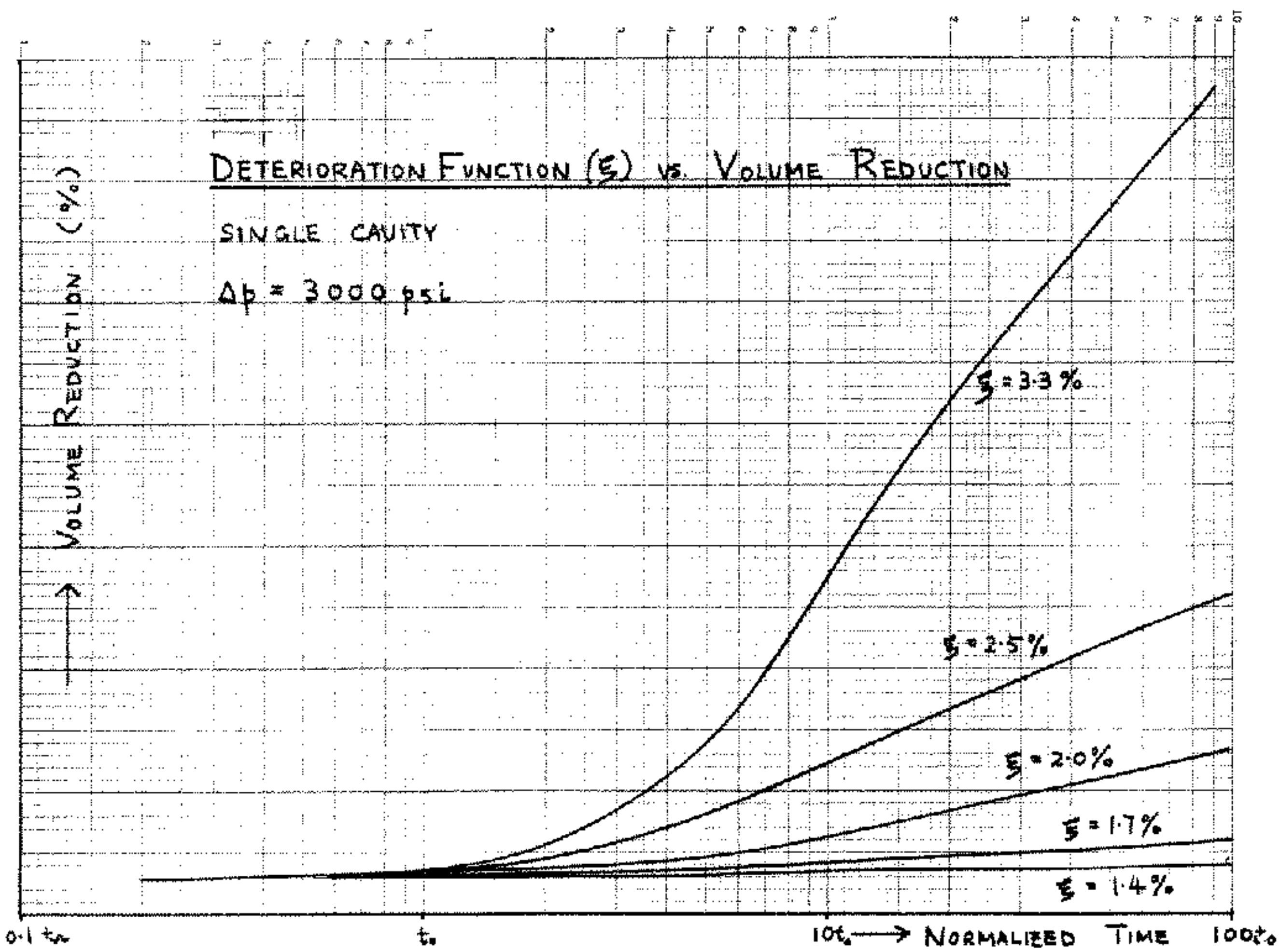

Figure 1. Relationship between Volume Reduction and Normalized Time (t/to) at Various Deterioration Functions (ξ) of Material Properties.

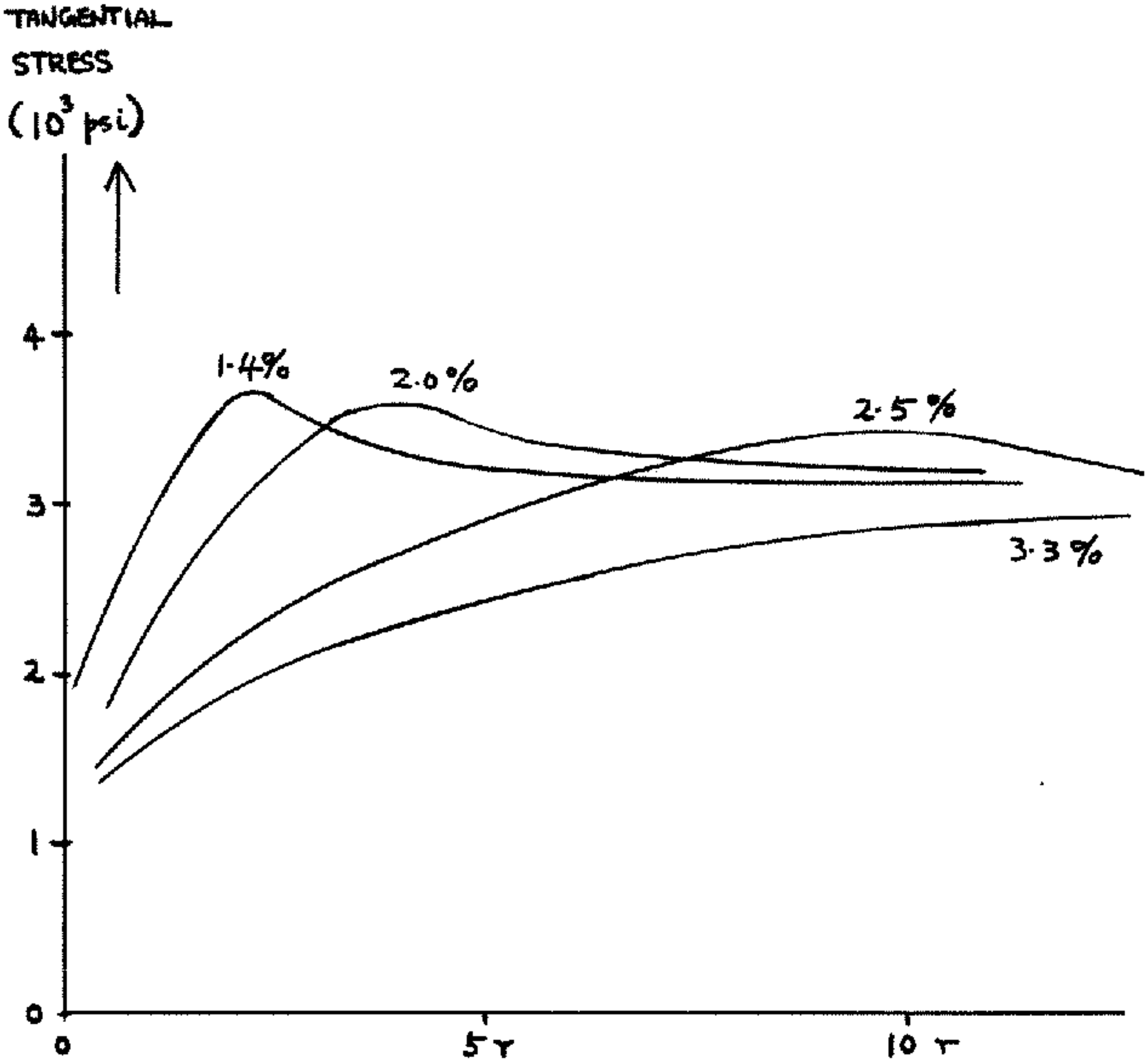

Figure 2. Stress Distribution Pattern in Ground Medium Around Cavity with Different Rates of Deterioration Function at $t = 100\, t_0$, r = radius of cavity; ΔP = 3000 psi.

wall, stretches out further at higher ε. As an example, for a material with ε of 1.4%, the plastic zone extends approximately twice the radius. For a different material with ε of 2.0%, the plastic zone extends four times the radius. When ε increases beyond 2.0%, the amount of the plastic zone increases rapidly. The creep continues even after the stress envelope stabilizes with time (Fig. 3).

DIFFERENTIAL PRESSURE

The differential pressure, that is, the difference between overburden pressure and cavity pressure, is an important parameter in determining the long-term creep behavior of underground solution cavities. This differential pressure is usually constant for liquid storage, being equal to approximately half the overburden pressure. Additional complications arise for gas storage because differential pressure can vary between zero and overburden pressure. Solid waste disposal presents the worst case, since the differential pressure is always at its maximum. Gas storage makes long-term creep evaluation more difficult because of fluctuating gas pressure levels.

There exists a critical differential pressure level for each individual salt cavity operation. This critical pressure level is specific to cavity depth, material properties and scheme of storage operation. Even when pressure levels subsequently fall below the critical pressure, creep continues for a long time before stabilizing again.

In design of gas and liquid storage cavities, it is desirable to predetermine the allowable range of cavity pres-

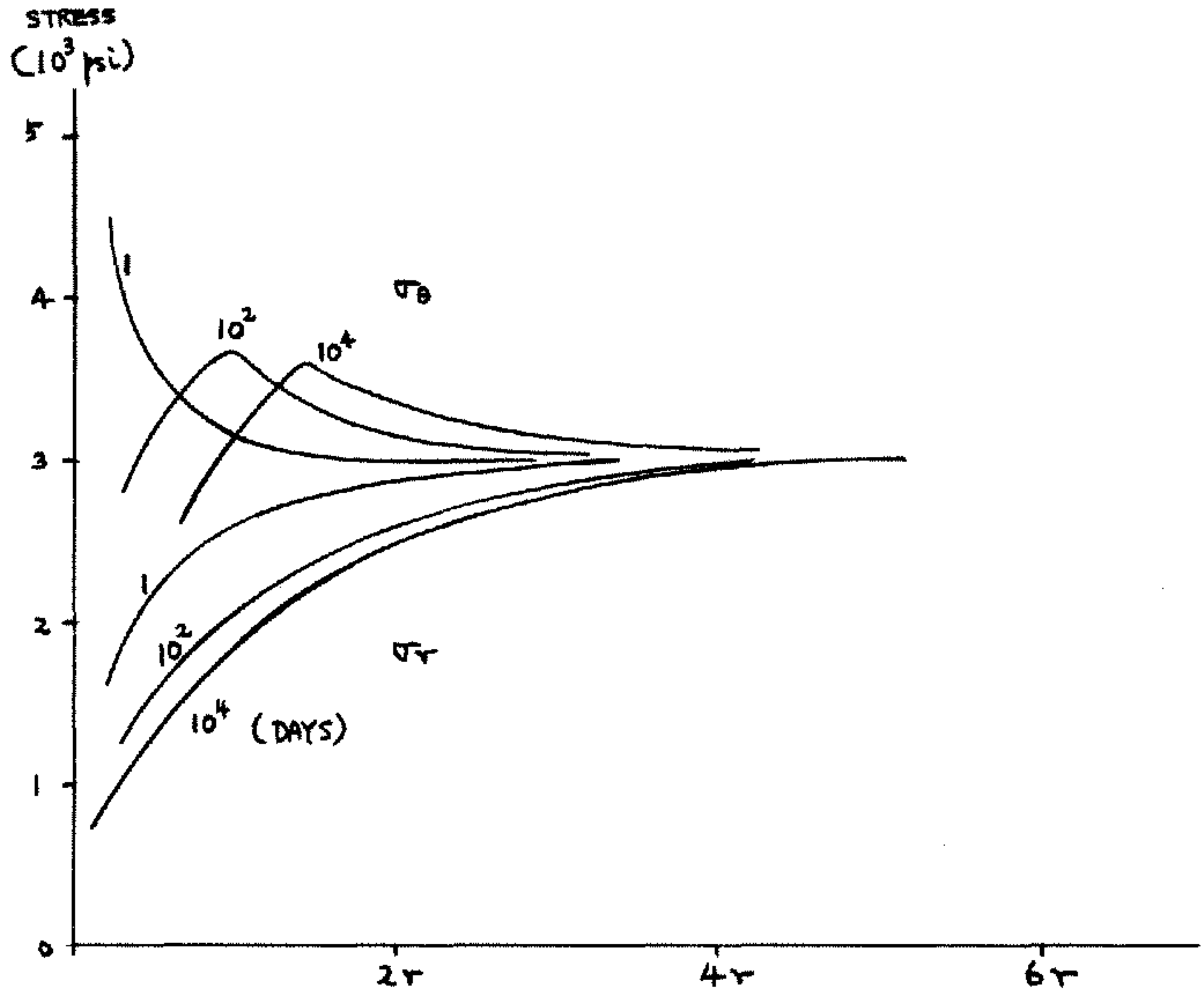

Figure 3. Change of Stress Distribution Pattern Surrounding Cavity with Cavity Age. r = radius of cavity; ΔP = 3000 psi; Deterioration function = 1.4%.

sure. This range is determined by the cavity depth and the maximum allowable differential pressure for the geology of given cavities. The upper limit of the allowable range is set by the overburden pressure while the lower limit is set by the amount of the overburden pressure minus the maximum allowable differential pressure.

It is this maximum allowable differential pressure that is determined by the deterioration technique. As shown in Figure 1, the acceptability of a certain differential pressure to a given cavity design is evaluated from the calculated relationship of cavity closure versus cavity age.

NUMBER OF CAVITIES

Another important factor in determining the long-term creep behavior of solution cavities, which has not been fully realized before, is the number of cavities in a system.

When more than a single cavity is created in a salt formation, each of the cavities suffer much greater creep deformation as shown in Figure 4. This factor is particularly important if the loading pressure is high. For instance, at a loading pressure of 5,000 psi, the normalized creep deformation for a single laboratory model cavity was 0.35×10^{-3} in. When three additional cavities were created around the cavity, normalized creep became 4.4×10^{-3} in.

A series of computer experiments comparing three systems; single cavity system, two-cavity system and three-cavity system was conducted. The cavity geometries are shown in Figure 5. The ground conditions and the material properties were set the same for all three systems. The results were summarized in Figure 6. For the single cavity system, creep deformation at normalized time $t = 100\ t_0$ was 13.4% which corresponded to a 26% decrease in

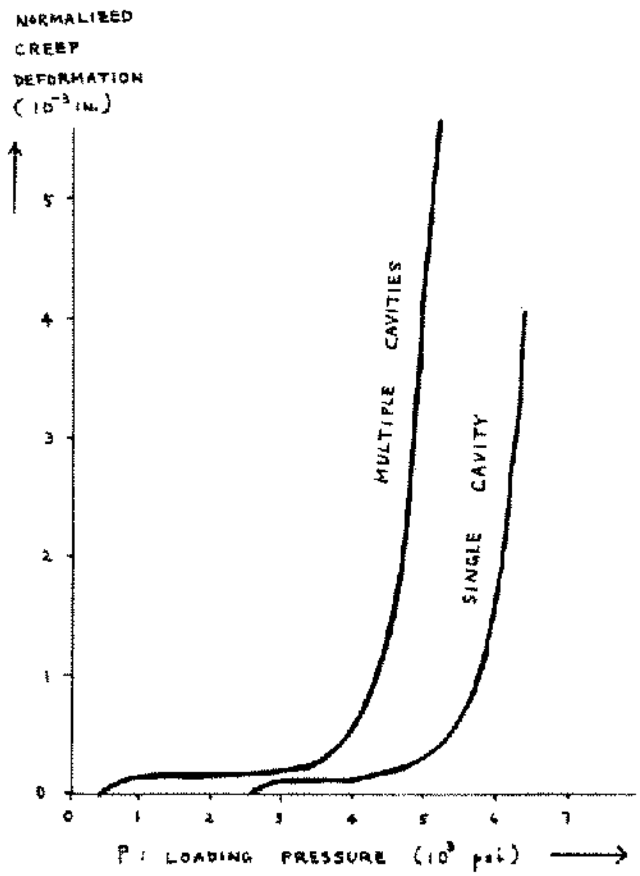

Figure 4. Effect of Number of Cavities and Loading Pressure on Creep Deformation.

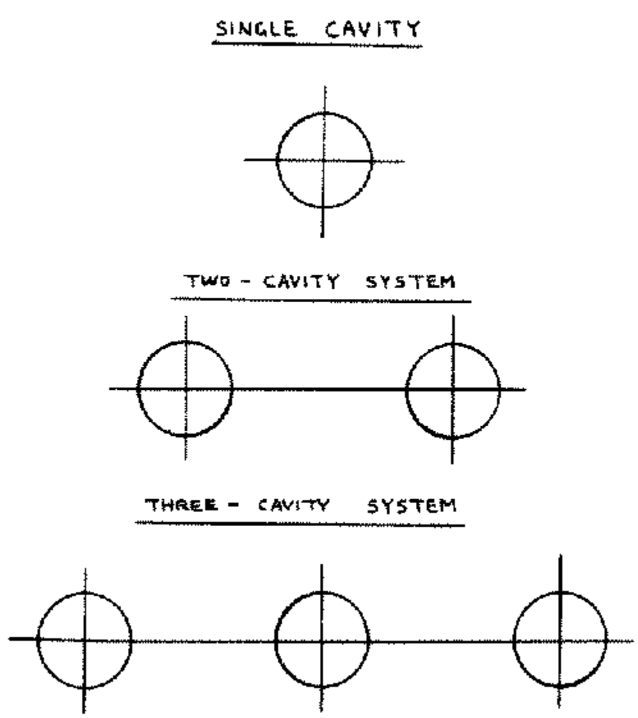

Figure 5. Geometry of the Three Systems in Computer Simulation Experiment.

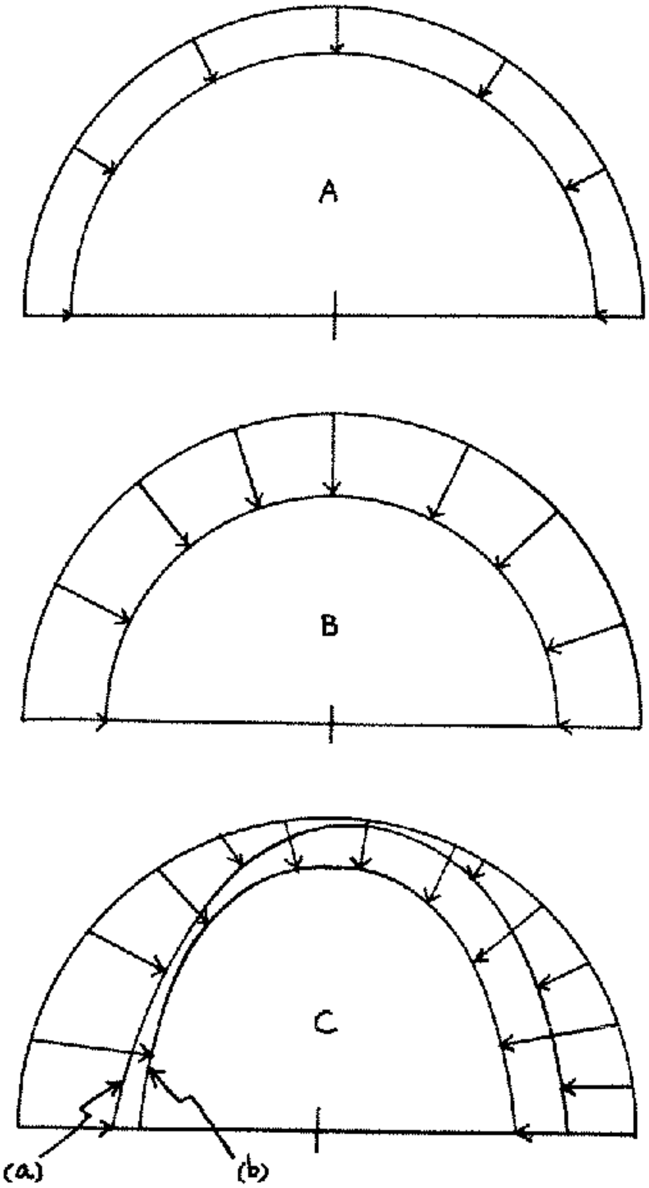

Figure 6. Comparison of Cavity Closures in Three Systems. ΔV = volume lost at normalized time $t = 100\ t_o$. (A) Single Cavity System $\Delta V = 26\%$; (B) Two-cavity System $\Delta V = 45\%$; (C) Three-cavity System; (a) outside cavity $\Delta V = 44\%$; (b) center cavity $\Delta V = 60\%$.

volume. In the two-cavity system, each cavity shrank by 26% at the boundary, resulting in a total volume reduction of 45%. This indicated strong interaction between the stress fields of the two cavities. The interaction effect was further increased by introducing a third cavity into the system, resulting in an overall volume reduction of over 49%.

The results of this experiment show that there was a definite relation between cavity closure and the number of cavities interacting with each other. In some cases this effect can be relatively minor whereas in others it is of importance. The interesting thing about cavity interference was the fact that cavity interaction increases with time. This is illustrated in Figure 7. By comparing the results of the three systems, it was found that initially there was little or no interaction. Each of the cavities in the three systems exhibited similar amounts of closure at the end of t_o. The difference began to show at 10 t_o. The single cavity shrank quite uniformly. Each cavity in the two-cavity system was slightly skewed, and had a radial closure twice that of the single cavity. The shapes of the cavities in the third system were badly distorted. The center cavity was shown in the figure for comparison to the other systems. The interference became more intense with time. After about 100 t_o, significant differences began to show up between the different systems. Such creep behaviors were verified with the available field data.

SEPARATION DISTANCE

Here another series of experiments was conducted, principally to determine the effect of separation distance between cavities in a two-cavity system. The important parameter is the separation ratio, S/D, which is defined as the ratio of the distance between the two cavity centers to the diameter of the cavity. S/D ratio was varied between 2 and 7 and the results of the experiment were summarized in Figures 8, 9, 10 and 11. It was found that the percentage of volume reduction increased with the reduction of separation ratio (Fig. 8). Figures 9, 10, 11 show the stress distribution pattern in the ground surrounding the cavities. The stress gradient increased with separation ratio decrease.

LARGE SCALE ANALYSIS

In analyzing long-term creep closure problems concerning solution cavities, it is also important to look into general problems such as permeability, heat conduction, overall cavity system stability and surface subsidence as illustrated in Figure 12. In this regard, it is particularly important to examine varied problems resulting from different ground conditions and cavity application. For a computer evaluation of the problems, they may be divided into two separate studies; one on inter-cavity behaviors in relation to the salt dome boundary and the other on the interaction between the salt dome boundary and the surrounding ground formations.

CONCLUSION

Basic parameters interact with each other and affect cavity closure in a highly nonlinear manner. The most important factors are identified as material coefficients and their deterioration functions, differential pressure and geometry. Their effects can only be analyzed effectively and realistically by adopting the hybrid model approach, partly theoretical and partly empirical. In development of

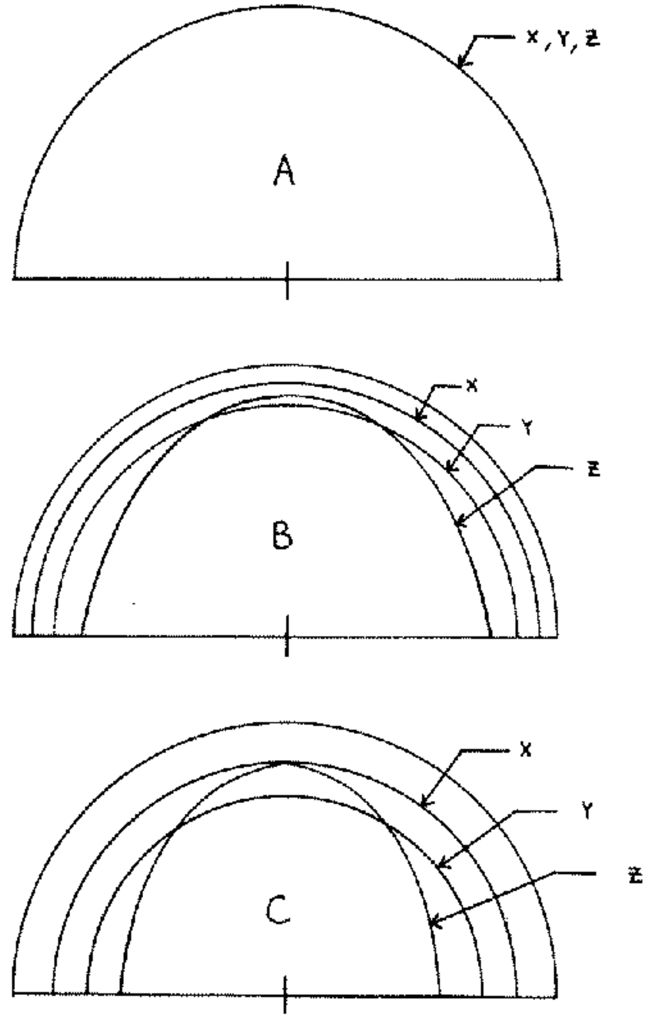

Figure 7. Comparison of Cavity Closure in Three Systems at Various Cavity Ages. (X) Single-cavity System, (Y) Two-cavity System, (Z) Three-cavity System, (A) Cavity age t_o, (B) Cavity age 10 t_o, (C) Cavity age 100 t_o.

this computer technique, a large quantity of controlled field data was utilized. The technique has been modified and substantiated to be in good agreement with past field data.

ACKNOWLEDGMENT

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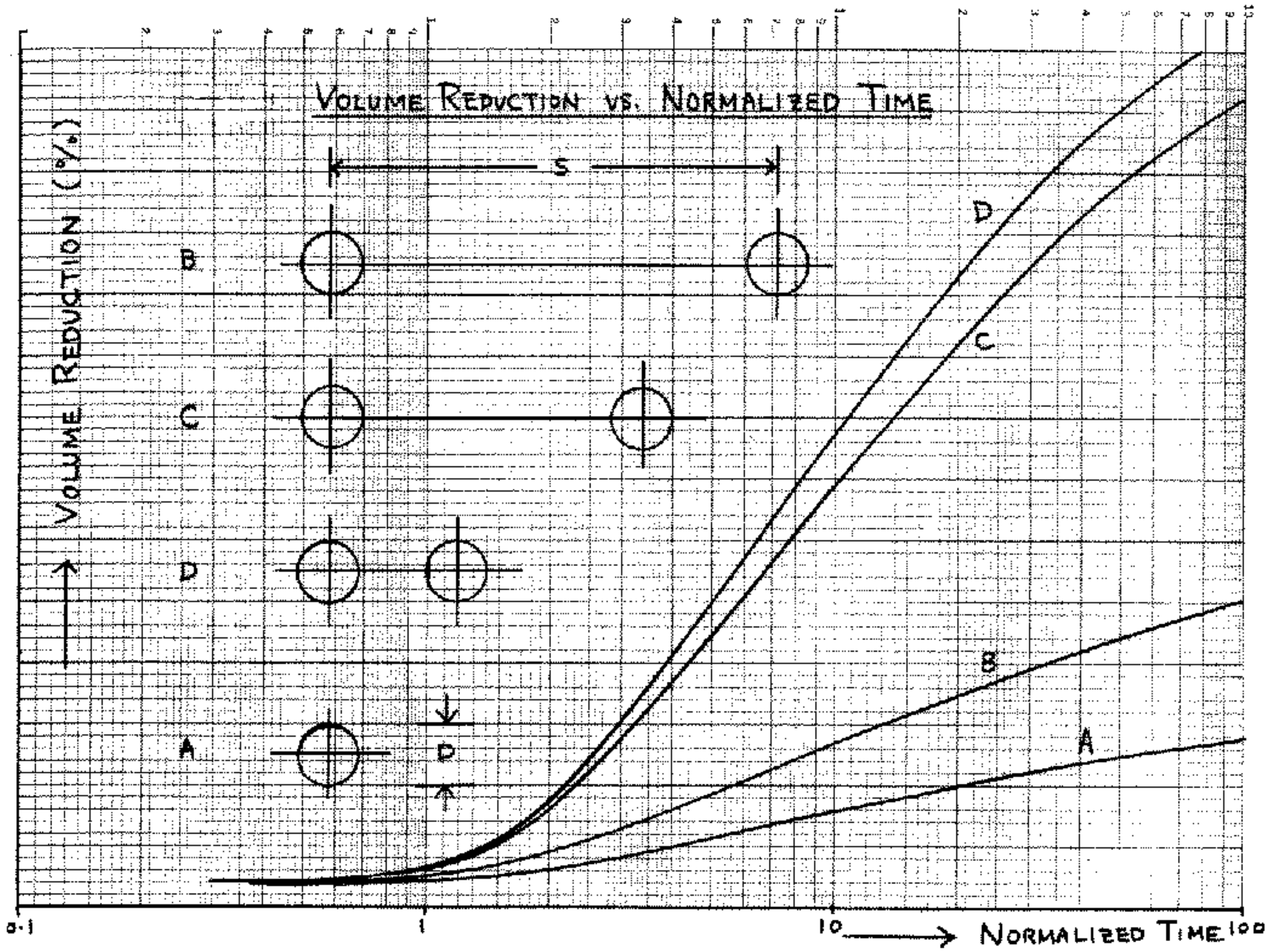

Figure 8. Volume Reduction Versus Normalized Time for Single Cavity and Two-Cavity Systems with Various Separation Ratios.

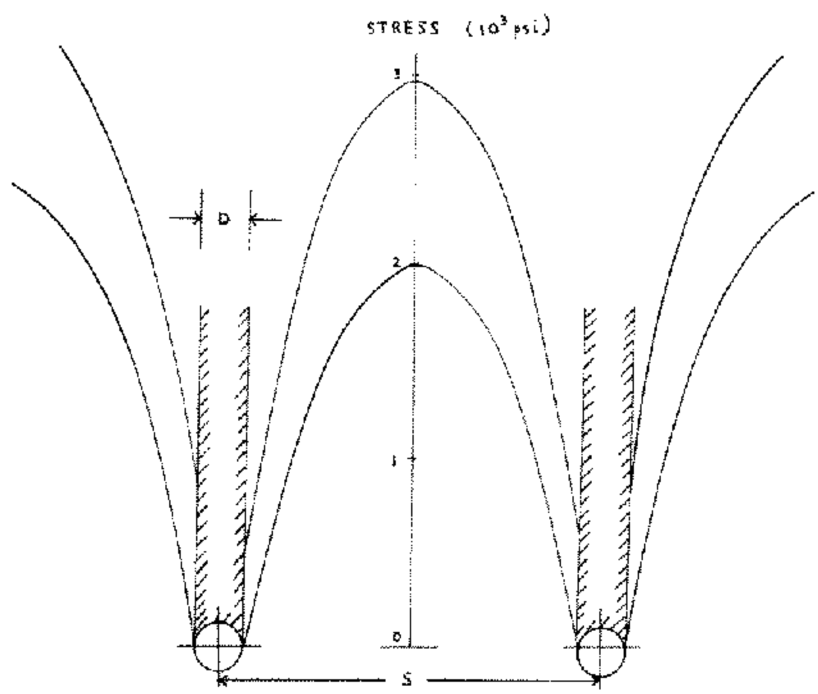

Figure 9. Stress Distribution Pattern in Ground Medium Around Two-Cavity System at 100 t_0 with S/D = 7.

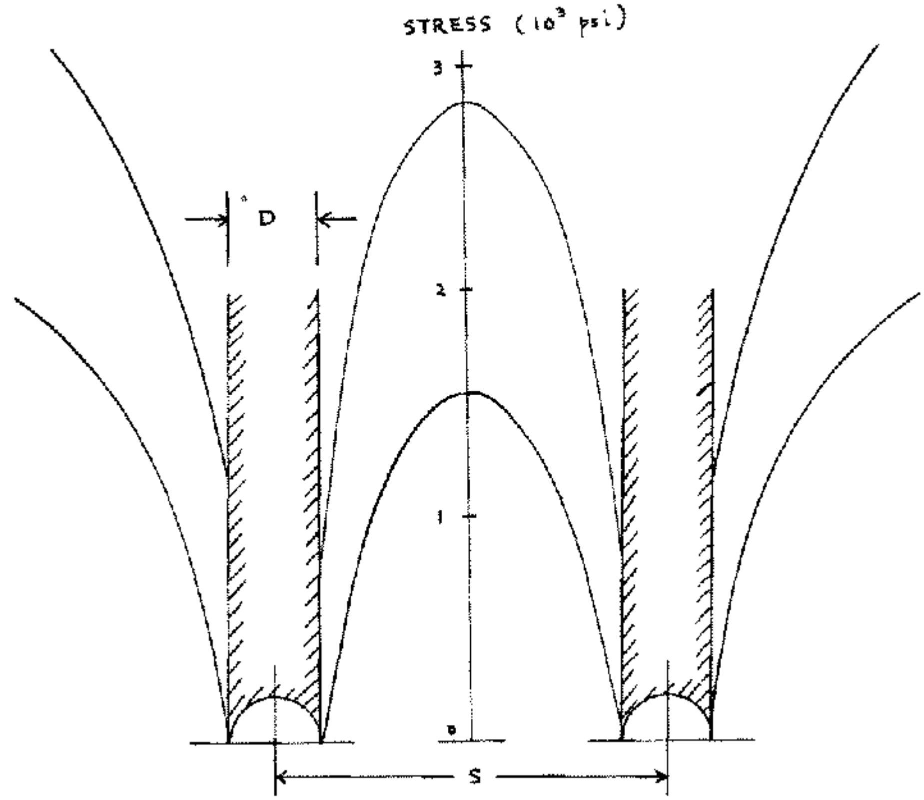

Figure 10. Stress Distribution Pattern in Ground Medium Around Two-Cavity System at 100 t_o with S/D = 4.5.

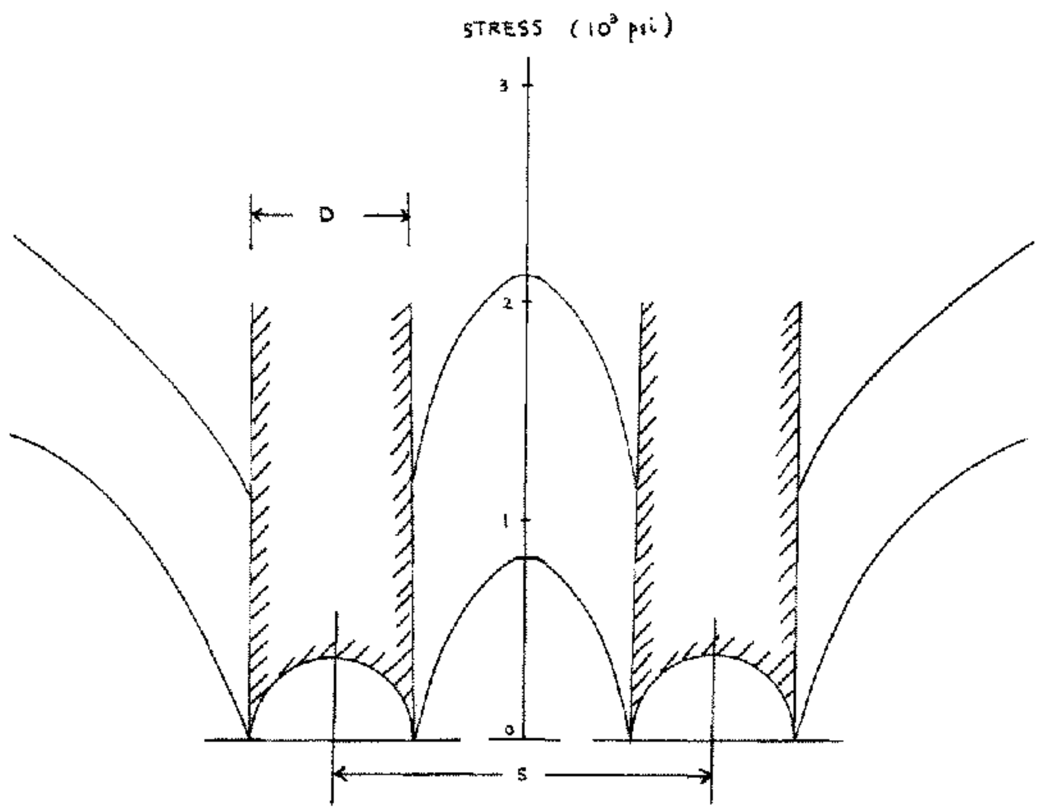

Figure 11. Stress Distribution Pattern in Ground Medium Around Two-Cavity System at 100 t_o with S/D = 2.

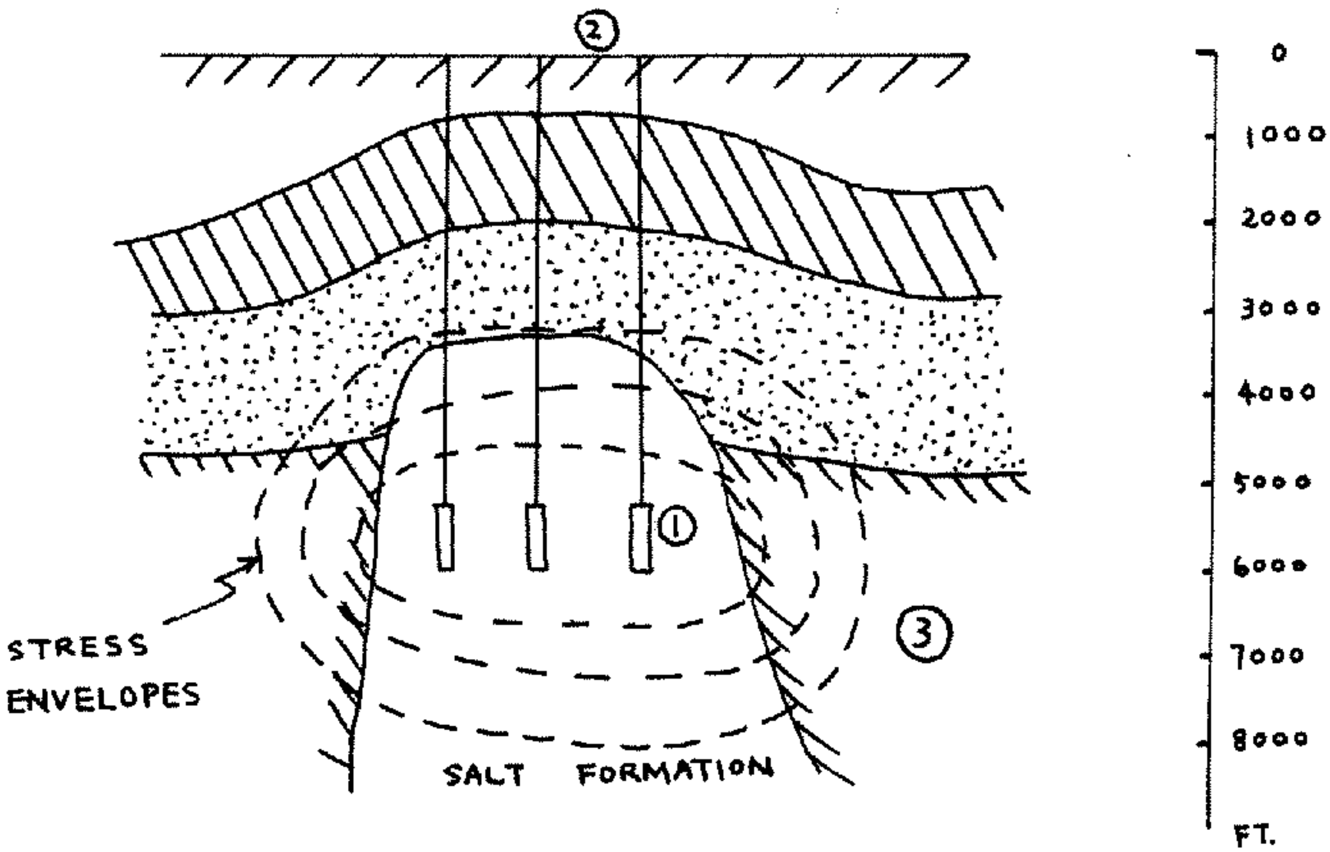

Figure 12. Large Scale Analysis of Problems that May Affect Long-term Creep Closure and Cavity Usage. (1) Cavity Stability (2) Surface Subsidence (3) Surrounding Ground Support to Salt Formation.

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METRIC CONVERSION

1 ft. = 0.305 m
1 psi = 0.0703 Kg/cm^2