Design Variables in Solution Cavities for Storage of Solids, Liquids and Gases

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ABSTRACT

The use of solution cavities for underground storage presents different design problems depending upon the type of material to be stored. Each type of material—solid, liquid, or gaseous—has peculiar effects upon the long-term rheological behavior of the rock salt boundary. The storage of natural gas or compressed air involves cyclic fluctuations of high gas pressures with corresponding reduction of the effective confining pressure on the rock salt surrounding the cavity. This results in gradual weakening of the rock media. Storage pressures for oil and other liquid products remain relatively constant at nearly hydrostatic levels, but the cavity wall is wetted. Storage of solids involves neither high pressures nor wet cavity walls, but due to the lack of confining pressure on the cavity boundary, the rock salt is subject to accelerated granular creep failure. Cavity design methods are dictated by the long-term rheological properties of rock salt and their interaction with the type of material to be stored. Field examples illustrate the different design methods.

INTRODUCTION

Underground salt cavities provide a safe and economical means of storing large volumes of a variety of materials in solid, liquid, or gaseous form. The importance of this storage medium has recently been appreciated because of the rising need to store energy-related materials such as radioactive waste, crude and refined oil, natural gas, and compressed air. Because the number of salt formations suitable for underground storage is limited, it is important that the design of salt cavities be efficient in terms of storage volume created and salt volume affected by creating the cavities.

Effective salt cavity design is also very much affected by the interaction of the stored material with the salt near the cavity boundary. For example, the loading condition at the salt boundary is different in all three cases of solid, liquid, and gaseous storage. In addition, other boundary variations in temperature, chemistry, and penetration of the stored material into the microscopic salt interstices may significantly affect the stability of the cavity. Finally, the design problem is complicated by the rheological nature of salt, and therefore, the boundary effects of the loading, temperature, permeability, etc., must be analyzed over the entire life of the storage facility.

SOLUTION CAVITIES—IDENTIFICATION OF DESIGN VARIABLES

Solid storage. Underground salt cavities used for storing solid materials generally have a constant pressure of one atmosphere acting normal to the cavity boundary, regardless of cavity depth and storage operation. Because of this small confining pressure, the rock salt is subject to accelerated granular creep failure. This is particularly true in mining applications in which room geometry may cause high lateral stresses in the salt immediately above and below the opening. The large shearing stress at the boundary caused by this high lateral loading may cause floor heave and roof collapse, which not only pose serious safety hazards, but also jeopardize the efficiency of the mining operation.

One of the most important proposed uses of salt cavities for solid storage is the disposal of nuclear waste materials. Research funded by the Atomic Energy Commission twenty years ago to develop design principles for nuclear waste disposal in underground salt cavities marks the transition from empirical to scientific design of salt cavities, and even today, extensive research is being done in this area. Numerous effects besides lack of confining pressure at the salt boundary need to be studied if reactor by-products are to be stored safely over the long time periods required for nuclear wastes to decay. These include temperature effects induced by the radioactive material, irradiation effects on the salt, water migration along thermal gradients induced by the radiation, and possible chemical reactions if the waste is liquid and escapes from its storage cannister. Though all of these effects have been studied individually over short time spans, further study of their simultaneous effects over very long time periods is necessary if safe radioactive waste disposal is to be practiced in the future.

Liquid storage. Virtually all solution cavities for liquid storage use the brine-displacement method of filling and emptying the cavities of the stored liquid. This procedure is illustrated schematically in Figure 1. The displacing brine is stored either in subsurface caverns, as shown in the Figure, or in surface brine ponds. The brine-displacement method insures that the liquid pressure at some depth D is at least as great as the weight of a brine column of height D. The actual liquid pressure on the cavity wall depends on the densities of the brine and stored liquid, depth, and the depth of the brine-liquid interface.

In designing solution cavities that use brine-displacement, the liquid pressure used is that which would exist if the cavity were full of brine, since that is the minimum liquid pressure and gives rise to the maximum differential stress between lateral earth stress and liquid pressure. Although the liquid pressure at a given depth will fluctuate as the cavity is filled or emptied, static rather than cyclic loads are generally used in the numerical analysis of liquid-filled cavities because both the cycle frequency and the magnitude of the resulting stress change are small in most applications.

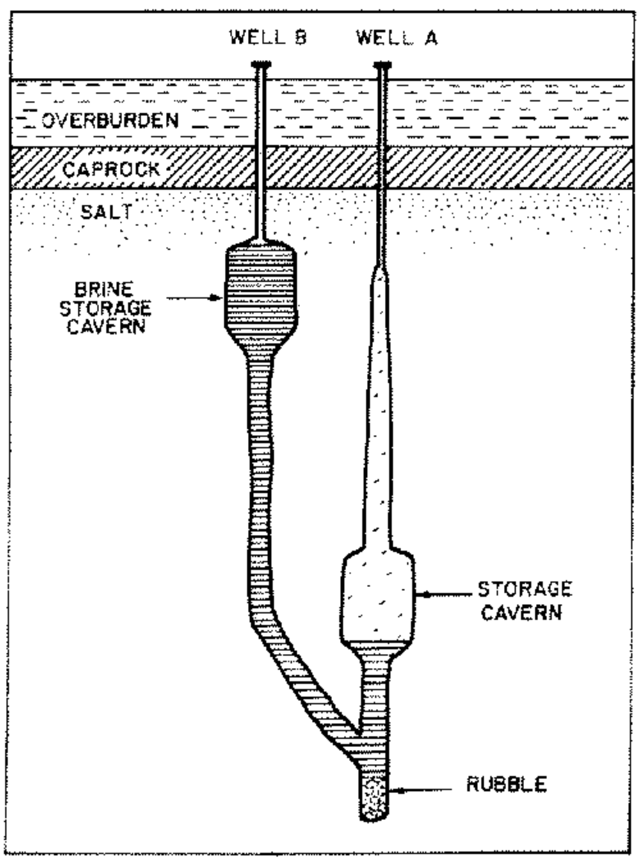

Figure 1. Brine-Displacement Storage Principle.

In addition to the liquid pressure on the cavity walls, consideration must be given to both the chemical and physical interaction of the liquid with the boundary salt. Chemical interaction might not only contaminate the stored liquid, but also dissolve the boundary salt, which could create an unstable cavity geometry. Similarly, penetration of the stored liquid into the salt interstices would reduce the effective confining pressure at the boundary which could lead to accelerated closure and ultimate failure.

The principal controlled variables in the design of liquid storage cavities in salt are 1) cavity dimensions, 2) cavity depth, and in the case of multiple cavities, 3) cavity spacing, and 4) cavity arrangement. The most efficient use of available salt space is made by packing the cavities hexagonally.

Gaseous storage. Gas storage in solution cavities is a relatively recent development, but promises to become more widely practiced in the near future. Numerous research efforts are currently in progress to determine the feasibility of compressed air energy storage (CAES), an electric utility application which permits storage in the form of compressed air of energy generated during low-demand periods and the regeneration of that energy during peak demand periods. In addition, gas companies are finding solution cavities and abandoned mines to be valuable large volume storage containers to help offset seasonal demand fluctuations.

Conditions at the boundary of salt cavities designed for gaseous storage are significantly different from those encountered in either solid or liquid storage. Of major concern are the long-term effects of the cyclic loading and of gas penetration on the structural integrity of the salt. Neither of these areas has been explored to date. Other important boundary conditions are the values of and ranges between maximum and minimum gas pressures and temperatures. It is clear that significant laboratory studies of the effects of these conditions, both individually and in combination with others, must be undertaken prior to widespread use of salt space for gaseous storage.

SOLUTION CAVITIES—RHEOLOGICAL DESIGN METHOD

A method has been developed for designing underground storage facilities in rheological materials such as rock salt. The three major components of the rheological design method are 1) in situ stress measurement, 2) rheological constitutive equations, and 3) a finite element representation of the rheological constitutive equations.

The rheological method is continuously being improved as new knowledge is acquired through laboratory and field studies. For example, laboratory test results on salt core samples might suggest a modification to the constitutive model, which is then coded into the finite element program. The modified program is used to analyze the specific mine or solution cavity geometry, and time-dependent displacements and stress distributions are calculated. The calculations are next compared with whatever field data can be collected, particularly from stress measurements and room closure data around mine openings or cavity closure data from solution cavities. Significant discrepancies, if any, between the field data and computer calculations are used to further modify the constitutive model. The many years that have gone into the development and continuous modification of the rheological design method have resulted in a reliable technique applicable to most types of storage in salt cavities and to design of mine openings in rheological materials such as salt and potash.

In situ stress measurement. A rheological stressmeter is being developed to measure in situ stress in time-dependent materials such as rock salt. This instrument has been successfully applied to distances up to 100 feet in the roof and pillars of Canadian potash mines, but will need some modification before it can be used where immediate ground access is not available, such as in deep test wells around solution cavities in a salt dome. In situ stress measurements using this instrument have proved practical in mining applications because only a single borehole is required, and measurements are quickly obtained so that many locations can be covered in a relatively short time period.

A schematic diagram of this instrument is shown in Figure 2. The instrument consists of a cylindrical probe with a pressurized and a non-pressurized section containing displacement transducers to measure borehole deformation, and supporting hydraulics and electronics for accurate pressure regulation and displacement recording. Deformation of the borehole in different directions is measured as a function

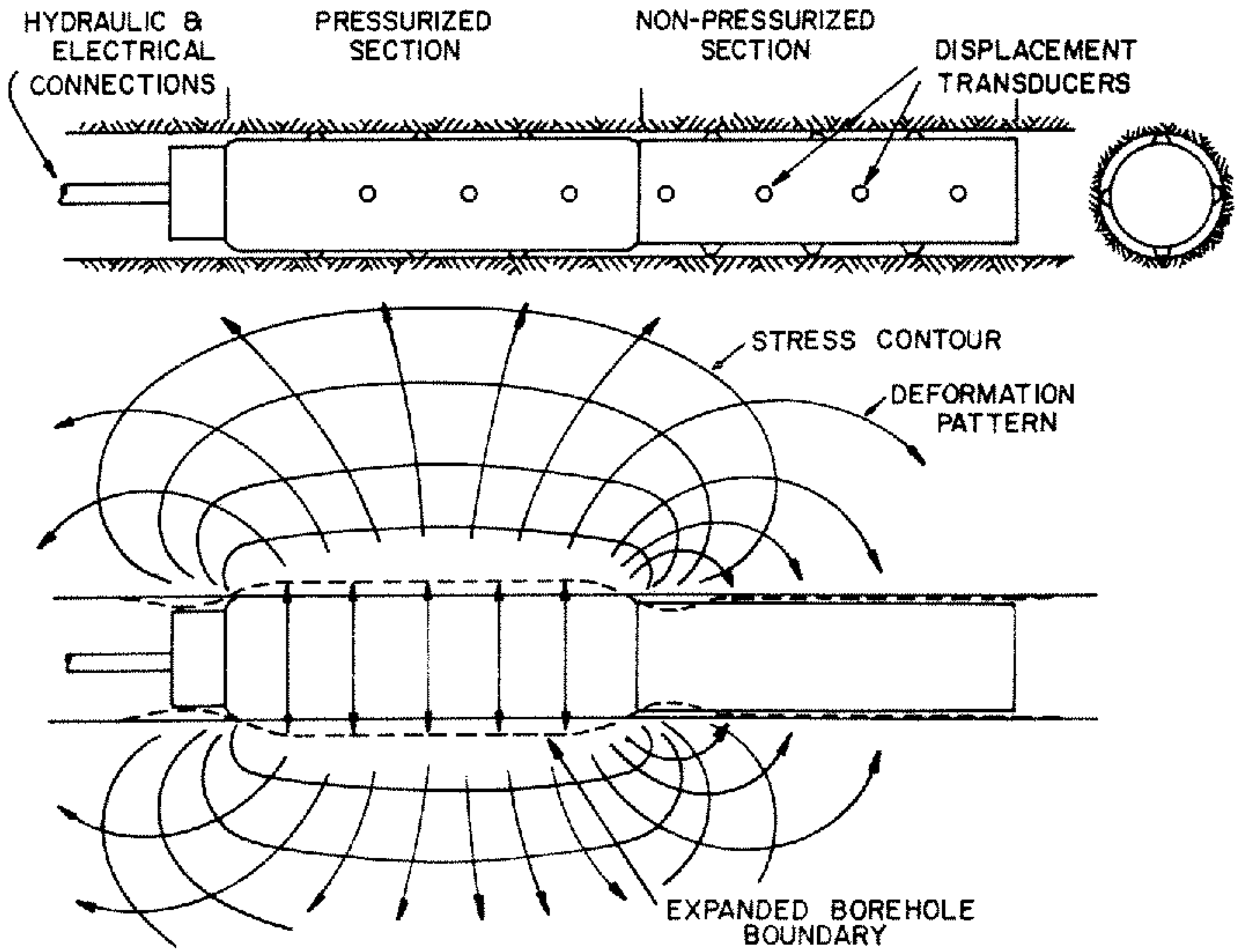

Figure 2. Schematic of Rheological Stressmeter (Patented).

of pressure and time. These deformations are then related to the in situ stress state through a finite element simulation of the borehole geometry and loading conditions. Rheological material properties of the salt which are needed for the computer simulation are obtained from laboratory creep tests.

Rheological constitutive equations. Geological materials are generally much more difficult to analyze in design problems than are most man-made materials, and rock salt is no exception. Two major difficulties in modeling rock salt behavior are the non-linearity of the stress strain curve and the strong tendency of rock salt to creep both viscoelastically and viscoplastically. On the other hand, however, rock salt possesses some very desirable qualities that tend to ease the modeling effort. For example, it behaves isotropically and usually is very homogeneous geologically, particularly in domed formations.

The main variables that affect rock salt behavior are confining pressure, temperature, octahedral shearing stress, and time. The effect of confining pressure is clearly indicated in triaxial test results shown in Figure 3, which also shows the non-linearity of the stress-strain relationship.

To predict rock salt elastic and creep behavior, the rheological model shown in Figure 4 has been developed. This model has elastic, viscoelastic, and viscoplastic components. For elastic analyses the model reduces to a two-property model using the bulk modulus K_1 and shear modulus G_1. These may be constants or, in non-linear problems, functions of the mean stress or some other parameter. In creep analyses the model behaves viscoelastically whenever the octahedral shearing stress is less than the octahedral shearing strength K_0 of the salt. When the octahedral shearing stress exceeds K_0, the salt flows viscoplastically at a rate controlled by the viscoplastic flow constant V_4. Laboratory studies have shown that the octahedral shearing strength of rock salt is not constant, but rather depends on such variables as confining pressure, temperature, and octahedral shearing strain. The dependence of K_0 on mean stress and octahedral shearing strain is shown in Figure 5.

The model is also flexible enough for accurate analysis of materials other than rock salt. The constants or functions in the model can be determined in such laboratory tests as

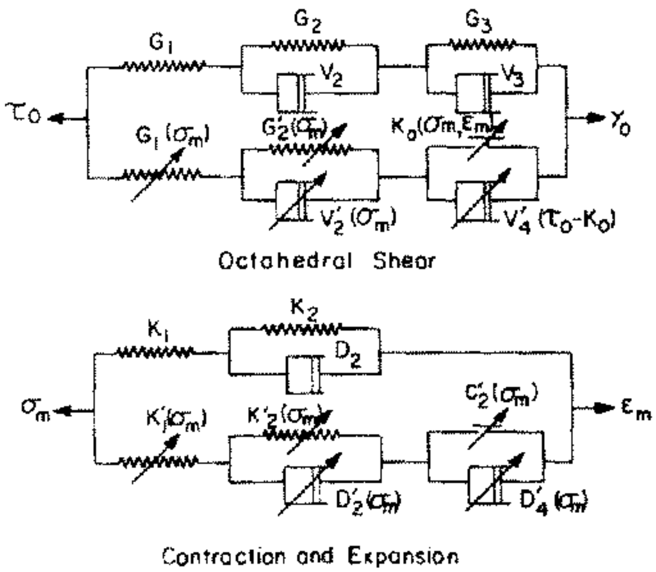

Figure 4. Rheological Model.

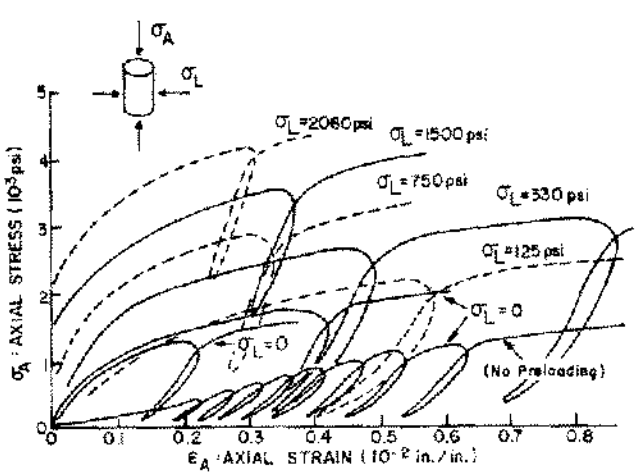

Figure 3. Triaxial Compression Test Results for Salt Hydrostatically Preloaded to 2000 PSI.

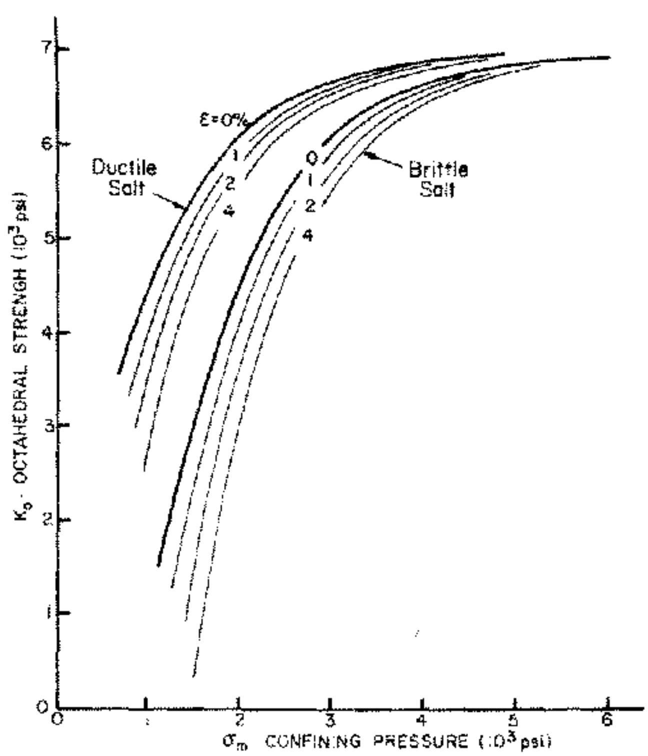

Figure 5. Octahedral Yield Strength Variation with Mean Stress.

direct shear, triaxial compression, and triaxial creep. The tests used and the loading conditions applied are chosen to best represent the expected field conditions.

Rheological finite element simulation. The rheological constitutive model described would be of little practical use were it not for advances that have been made in the past twenty years in numerical analysis techniques such as the finite element method. Thus, a finite element representation of the constitutive equations has been developed so that a wide range of geometric, loading, and initial stress conditions can be analyzed routinely in the design of mine openings or solution cavities. Also, since the flexibility of the model permits accurate representation of a wide range of materials and not just rock salt, clay seams and other bedded formations above a mine opening, shale and sandstone formations on the flank of a salt dome, and other geological complications can be included in the analysis.

Besides its use in prediction of stresses and displacements around underground openings, the computer simulation technique may also be used to indirectly estimate the in situ stress state around the opening if other parameters are known. For example, if the boundary displacements of a mine opening are measured and the properties of the materials influencing the displacements are investigated in the laboratory, the in situ stress state may be varied in a sequence of computer analyses of the mine geometry. The computed and measured displacements can then be compared to evaluate the validity of each in situ stress state assumed. After the difference has been minimized, the best estimate of the in situ stress can be used to explore other mine designs which may be more economic, safer, and/or more efficient operationally.

RHEOLOGICAL METHOD—APPLICATIONS

Storage of solid matter. The most important use of salt cavities for future solid storage is likely to be the disposal of nuclear waste materials. Reactor by-products pose very serious contamination threats many thousands of years after they are created, and hence, a very stable environment that offers sufficient shielding must be provided if nuclear fission is to become a prominent energy source. Because of the self-healing nature of confined rock salt, cavities and mines in salt have been considered for about twenty years as possible disposal sites, and many research studies are still in progress.

Despite this research effort, there are as yet no such facilities in operation. The rheological method has been used, however, to design underground salt and potash mines in which the opening is confined only by the pressure of the atmosphere. This condition would also prevail at a radioactive disposal site. Three different design methods based on rheological principles have been developed for application in a wide range of geological conditions. These three methods, which collectively are called the Stress Control Technique, are the stress relief, parallel room, and time control methods. The ground condition for which each is best suited is described in Table 1.

The stress relief method is used in uniform ground where no separation seams are present in the immediate roof or floor. The principle of this method is to improve room stability by widening the room rather than reducing its width. As shown in Figure 6, this reduces the lateral stresses in the immediate roof and floor and redirects the high lateral stresses into regions further removed from the opening where their adverse effects are substantially reduced. It is important, however, that the ground subjected to these increased lateral stresses is competent. This method has been used successfully at the Rocanville mine of the Potash Corporation of Saskatchewan, where rooms have been widened over the years from 67 to 85 feet, and at Diamond Crystal Salt Company's salt mine in the Jefferson Island salt dome, where rooms have been widened from 80 to 160 feet with simultaneous improvement in ground safety, operational efficiency, and extraction ratio.

The principle of the parallel room method is shown in Figure 7. A second room is excavated close and parallel to a failing first room. This second room is protected by a secondary stress envelope that develops around the two rooms. The process can be repeated for additional parallel rooms until a limit determined by the properties and stratigraphy of the overburden formations is reached. The parallel

TABLE 1

Three Methods of the Stress Control Technique

Method	Ground Condition	Recommended Uses
Stress relief	relatively uniform ground media without dominant separation seams; natural roof fall in 0.5 to 10 years	general underground mining
Parallel room	weak ground due to non-uniformity and stratification of the ground media; natural roof fall in 0.5 to 10 months	mining in weak sedimentary formations
Time control	highly stratified, weak ground media due to numerous separation seams; natural roof fall in 0.5 to 10 weeks	mining in quickly failing ground

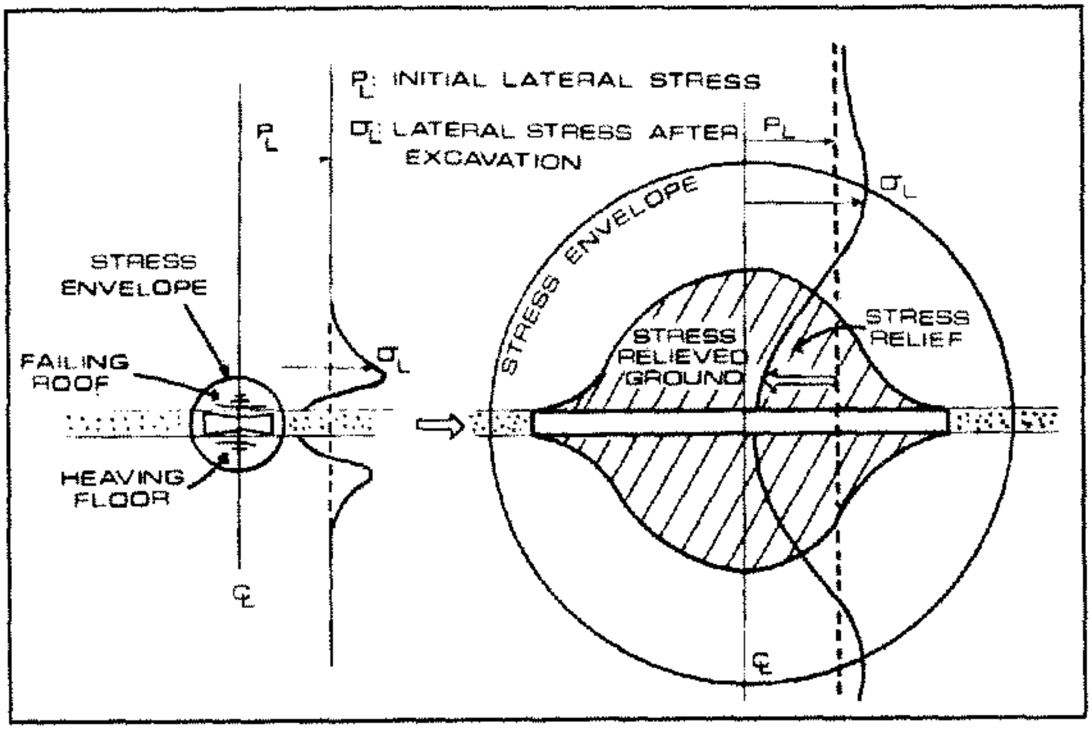

Figure 6. Stress-Relief Method.

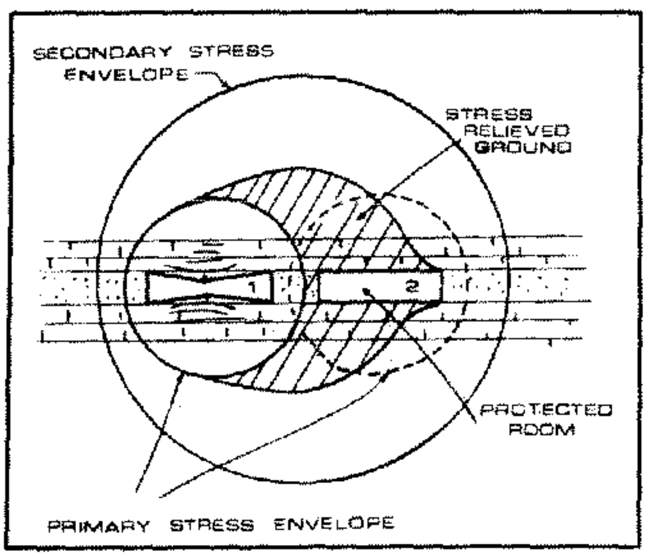

Figure 7. Parallel-Room Method.

room method has been used successfully in other Saskatchewan potash mines such as the APM Operators Allan mine and Cominco's Van Scoy mine, which both have more overburden discontinuities than the Rocanville mine.

The time control method differs from the first two methods in that a specific time sequence is used in excavating a group of parallel rooms. Figure 8 shows the principle of the time control method applied to a three-room system. The two outer rooms are created first, sufficiently far apart to allow individual primary stress envelopes to form around each, which causes overloading and strain-hardening of the ground between the two. A third room is created some time

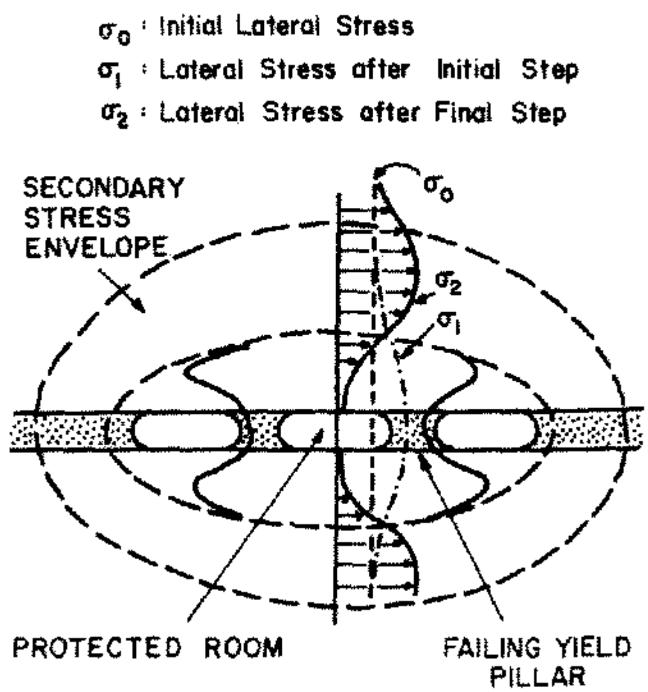

Figure 8. Time Control Method.

afterward in this strain-hardened ground. The two pillars between the three rooms fail as soon as the center room is created, transforming the three primary stress envelopes into a single secondary stress envelope which stabilizes the center room and improves the stability of the two outer rooms. Successful applications of the time control method have been made in the APM Operators Allan mine and the Potash Corporation of Saskatchewan's Saskatoon mine. The time control method is patented in the United States and Canada.

Liquid storage. Solution cavities have been used successfully for storage of crude oil and petrochemical products, as well as for brine production. The economic importance of storage space in salt has necessitated more efficient design to maximize total storage volume for both current and future needs. This is not only because salt space is a limited natural resource, but also because some of the available space is not conveniently located in terms of the distance and means of transporting the stored material to and from the storage facility.

An example of the application of the rheological method to maximize storage capacity in a salt dome is analysis currently in progress for the Louisiana Offshore Oil Port (LOOP). Seventy million barrels or more of crude oil are to be stored in the Clovelly Salt Dome (Louisiana) in 14 cavities of 5 million barrels each, with the potential of increasing that total volume by solutioning additional cavities at a later date.

Preliminary computer analyses exploring a wide range of parameters have been supplemented by laboratory test data of core samples taken from a borehole from the surface to the depth of 2,750 feet. Properties of rock formations on the flanks of the dome were estimated from published studies on similar materials in the Louisiana Gulf Coast area. However, reliable in situ stress measurement techniques have not been developed for application in deep wells drilled from the surface. Therefore, a wide range of possible initial stress states are being investigated as part of the parametric studies.

Figure 9 shows the generalized geology of the Clovelly Dome and a proposed 19-cavity hexagonal layout is shown in Figure 10, together with the finite element idealization used for this analysis. The salt dome is nearly circular in cross-section with a radius of about 1,600 feet at the 1,500-foot depth. The center-to-center separation distance will be approximately 570 feet. Final cavity diameter has not yet been determined, but will probably be between 190 feet and 250 feet. The top of the cavities will be at approximately 1,500-foot depth, leaving a 300-foot salt thickness above the cavities, and 300 feet of salt will also separate the outermost cavities from the salt dome boundaries.

Parametric studies of the effects of different values of in situ stress state, cavity diameter, octahedral shearing strength of salt, and material properties of the flank rock have indicated that the in situ stress state in the salt is the dominant parameter controlling cavity closure and boundary strain. It has been shown theoretically that the lateral stress S_L in a stable salt formation is related to the vertical stress S_Z and the octahedral shearing strength K_0 of the salt by the relationship:

$$S_Z - (3/\sqrt{2})K_0 \leq S_L \leq S_Z + (3/\sqrt{2})K_0$$

Most of the computer analyses completed above have used the most conservative assumption of maximum in situ lateral stress, although other cases ranging from hydrostatic to maximum were also analyzed. Results indicate that volume losses of 20% to 30% in the first 30 years of operation may occur if the in situ lateral stress is maximum, but overall volume losses should not exceed about 5% if the lateral stress is not significantly greater than the overburden pressure.

Pressurized gas storage. The first application of the rheological design method for analysis of caverns for storing pressurized gas was done in the early 1970's for the Transcontinental Pipeline Corporation (Transco). At that time Transco's two storage cavities, which extended between the depths of about 5,700 feet and 6,600 feet in the Emminence Salt Dome (Mississippi), had suffered large unexpected volume losses of about 40% in the first year of operation. Subsequent computer analysis of the behavior of the cavities indicated that viscoplastic deformations during solutioning and particularly during the first gas pressure unloading cycle were the cause of the large closure. In addition to the large volume loss, a sonar survey indicated that the floor of the gas cavities had apparently risen about 120 feet (see Figure 11). It was suspected that much of the boundary salt had failed and fallen from the walls to the cavity floor. This was believed to have occurred because of gas penetration into the intergranular spaces in the salt, which reduces the effective confining pressure at the boundary. To create additional storage space, two new cavities were later solutioned, and one of the two original cavities has since been solutioned upwards.

The storage caverns for the world's first large-scale compressed air energy storage (CAES) plant in Huntorf, West Germany were also analyzed using the rheological method. This plant stores off-peak energy by compressing air in two underground solution cavities. The compressed air is later heated and expanded through turbines to drive a generator to supply electric power during peak demand periods. The two caverns were designed to be about 50 meters in diameter and are separated by about 210 meters of salt. Volume losses due to inward flow of the salt were computed to be about 3% in the first 30 years of operation.

There is much interest today in CAES in the United States where numerous research projects are already in progress. The success of the Huntorf plant will be closely monitored. In particular, unpredicted boundary behavior

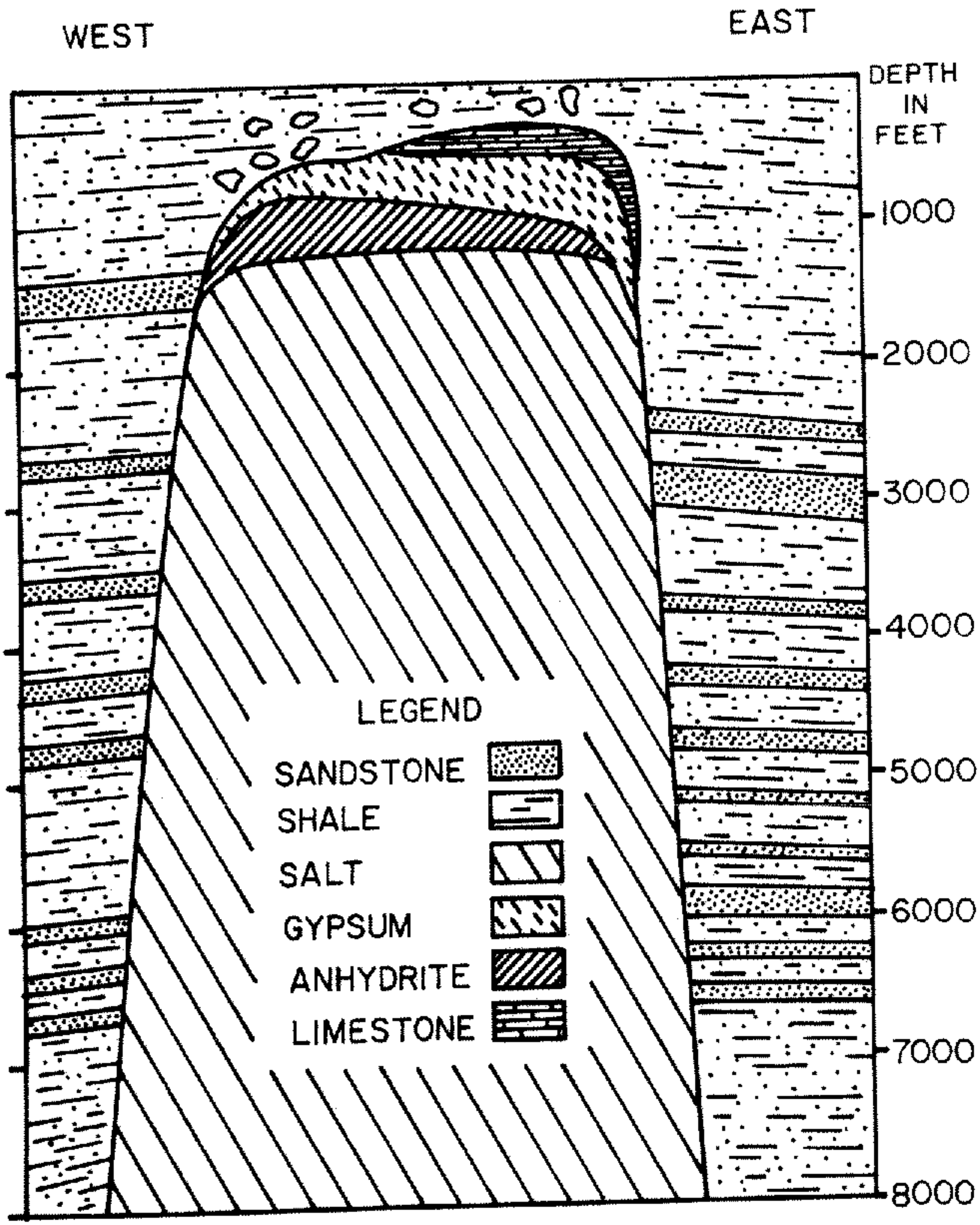

Figure 9. Geology of Clovelly Salt Dome.

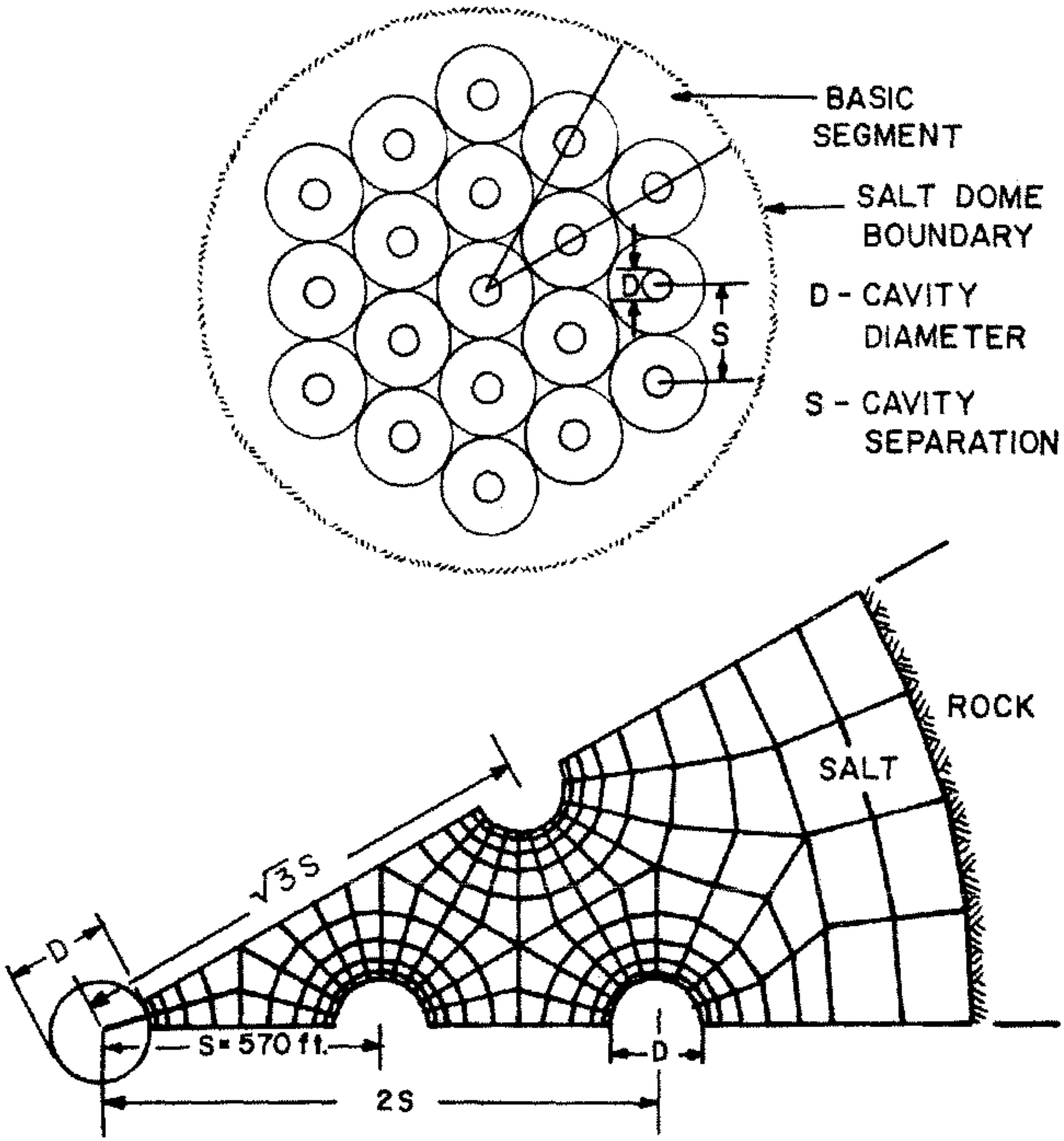

Figure 10. 19-Cavity Network with Finite Element Idealization.

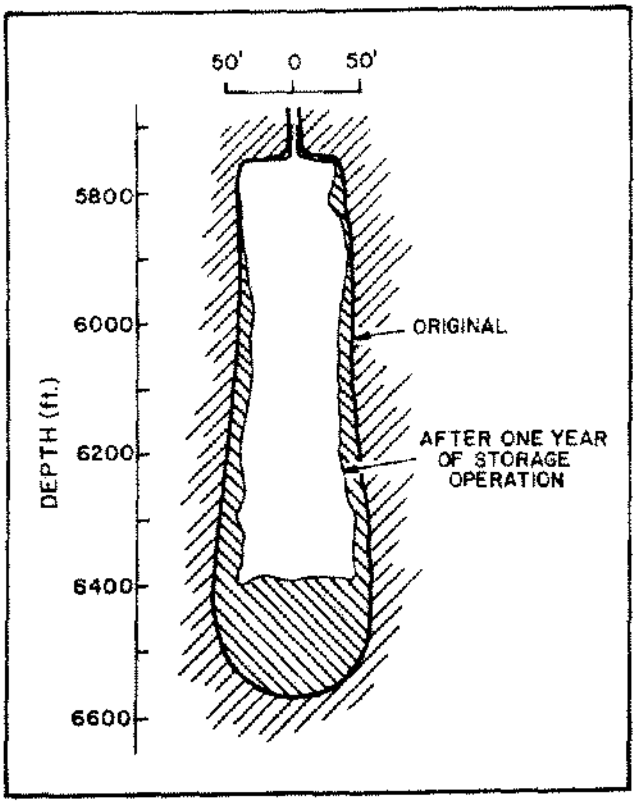

Figure 11. Geometry of Emminence Dome Gas Storage Cavity.

could help to identify areas of future research in the laboratory testing of rock salt. These areas might include the response to daily cyclic loads and the penetration of the compressed air into the salt interstices, which could reduce the intergranular bonding strength of the salt near the boundary substantially.

DISCUSSION

Dr. Velzeboer.

Question. Is deterioration caused by the cyclic loading of gaseous matter in the salt cavities?

Answer. Yes, you are right in that the deterioration is caused by the cyclic loading of gaseous matter in salt cavities. However, there are three important things to be appreciated in gas storage. First, compressed gas penetrates into the surrounding salt media of which extent is much greater than that of any form of liquids. Secondly, the gas penetrates into the strained media of cavity boundary resulting in reduction of effective stress, which in turn becomes the direct cause of boundary failure. Finally, there was a substantial amount of viscoplastic flow of the salt itself contributing to the cavity closure.

Dr. Th. H. Wassmann.

Question. Can you cite the reasons for the closure?

Answer. There are two reasons for the closure: 1) Viscoplastic flow and associated volume expansion; and 2) Granular deterioration of the boundary salt media resulting in volume expansion. There was no measurable surface subsidence over the cavities.

To my best recollection, the temperature gradient is normal, which means that there is an approximately 20°F increase per 1,000 feet of depth increase.

Dr. K. Wahi.

Question. Do the illustrations all come from the same mine? What specifically is meant by creep strength?

Answer. No, all the pictures come from many different mines. However, for the purpose of the intended comparison, there is no importance on where they are from. All the protected rooms are stabilized beautifully with no roof bolts as shown, regardless of how badly they were failing before the application of the Time-Control method.

The creep strength is meant to be more specifically octahedral shearing strength. The strength will be determined from long-term triaxial creep tests by separating viscoelasticity, viscoplasticity, elasticity, and volume expansion from the total creep deformation. For more detailed information, please refer to my previous publications, particularly to our paper by Serata, Sakurai, and Adachi, "Theory of Aggregate Rock Behavior Based on Absolute Three-Dimensional Testing (ATT) of Rock Salt", proceedings of the Tenth Symposium on Rock Mechanics, University of Texas, Austin, April 1968.

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