Utilization of Stress Envelopes in Design of Solution Cavities

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ABSTRACT

For the first time, a method was developed by the author to measure accurately and effectively in situ stresses in nonelastic media such as rock salt. This has been accomplished through 10 years of field research in the development of Saskatchewan potash mines. The stress distributions measured in potash and salt mines disclose the presence of distinct stress envelopes and their unique characteristics. By utilizing this unique behavior of the stress envelopes, solution cavities can be designed for greater capacity and stability. The design method is illustrated by using actual examples of solution cavities created in bedded salt underlying a weak shale formation.

INTRODUCTION

The recent development of Saskatchewan potash mining required a truly scientific approach to their rock mechanics problems. The problems are difficult ones because the mining depths are all greater than 3,000 ft. and their geological complications include the presence of high pressure aquifers above the mining horizon. The locations of all the potash mines developed in the last 12-year period are shown in Figure 1. Each point in the map represents one mine which required an investment on the order of 100 million dollars, forming a total one billion dollar industry. The design technique described in this paper is a product of the rock mechanics research carried out by my laboratory with the close cooperation of this industry.

Large ground movements were observed in all the potash mines; yet the nature of the movement was found to be very specific to the individual mine conditions. It was quickly demonstrated in the mines that creep measurements alone are not sufficient to understand the total behavior of the underground. The creep movement of the underground was shown to be merely a reflection of the existing stress condition. The stress is the cause of the underground movement which should be determined first. With this realization, the development of an in situ stress measuring method was considered the first goal of the study.

Before this method was developed, solution cavities were designed mainly through lessons learned by field experiences with very little understanding of the geomechanics of the cavities. The stress envelope technique can now be used for designing new solution cavities with careful evaluation of their long-term effect on the ground surface. It can also be used for evaluating existing cavities. The new technique still needs further refinement, particularly to handle the actual diversified geological conditions by using the computer method which was developed specifically for this purpose. This refinement work is now in progress with improvement of the basic technique which is described below.

STRESS RELIEF METHOD

An interesting relationship between the room width of an underground opening and its roof stability was established through many years of systematic observation in potash mines. When relatively narrow rooms of 16–24 ft. in width were made in potash mines, the rooms in production panels suffered extensive roof separation regardless of the competence of the roof formation. This roof failure was caused by the high stress concentration zone formed immediately above the roof as illustrated in Figure 2.

The same roof formation was greatly stabilized by widening the room width from 21 to 67 ft. This was found through numerous tests conducted over an extended period of time. The roof stability was further improved under the same extraction rate when two of the 67 ft. rooms were placed parallel, close together, by reducing the sepa-

Figure 1. Location of 10 Saskatchewan Potash Mines in Canada.

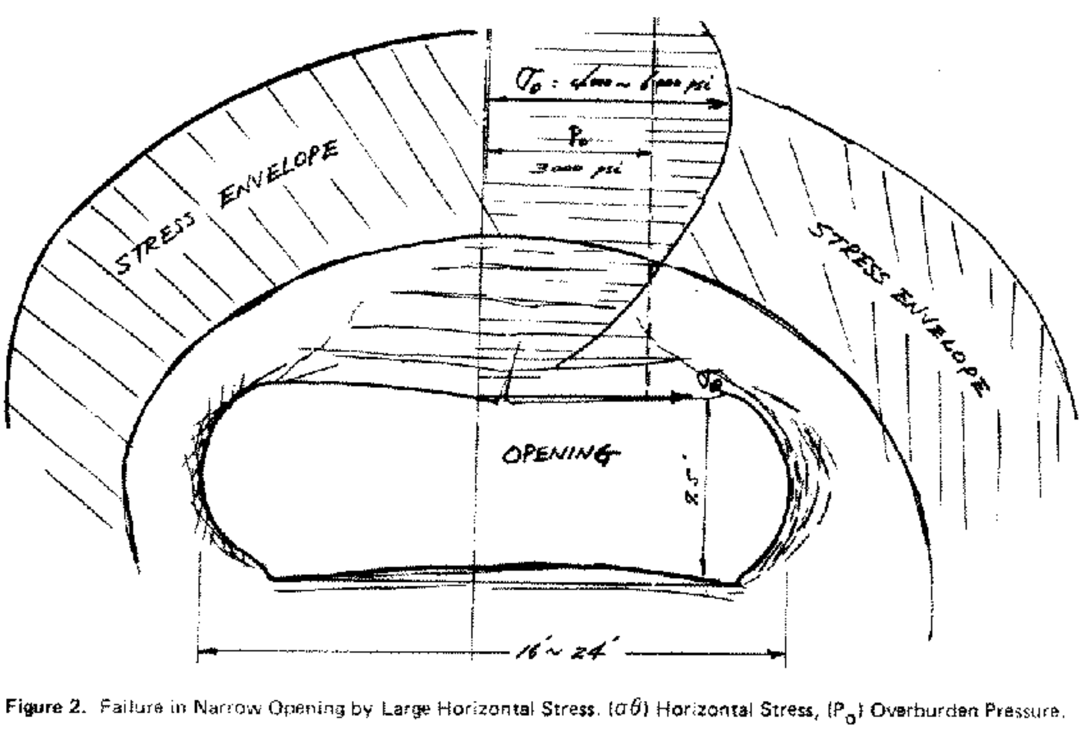

Figure 2. Failure in Narrow Opening by Large Horizontal Stress. ($\sigma\theta$) Horizontal Stress, (P_o) Overburden Pressure.

ration pillar width from 160 to less than 60 ft. as shown in Figure 3. It was found from the in situ stress measurements that the improvement of the roof stability was caused by the location of the stress envelope relative to the exposed roof. With a larger room width, the location of the high stress concentration point is moved upward, away from the exposed roof, resulting in a smaller stress gradient as illustrated in Figure 3. Under the same extraction rate of 35%, closures of three different rooms were compared, and wider rooms were found to be more stable than narrower rooms.

Whenever a room is created immediately next to an existing room or a group of rooms, the original stress envelope expands to include the newly created one. In the process, the newly created room receives the advantage of stress relief effect. This scheme of providing roof protection is called the Stress Relief Method which can be effectively utilized for designing solution cavities. This scheme is illustrated by the stress distribution around two rooms described in Figure 3.

STRESS CONTROL METHOD

The Stress Control Method is a technique for creating a large stable cavity by regulating more than two stress envelopes in a certain time sequence. The Stress Control Method is different from the Stress Relief Method in the manner of forming the final protective envelope. It is generally more effective in roof stabilization than the Stress Relief Method.

The Stress Control Method is explained in Figures 4 and 5. At first, two pre-stress openings are created. A stress envelope is formed around each opening. This is called a primary stress envelope, as shown in Figure 4. These two openings are placed sufficiently close together so that the ground between these two openings is subjected to additional compression for strain hardening. Then through the strain-hardened ground, a third opening is created to form a protected room as shown in Figure 5. The two pillars (narrow walls) thus created are made to yield quickly at a predetermined rate so that the three primary stress envelopes suddenly transform into one single envelope. This

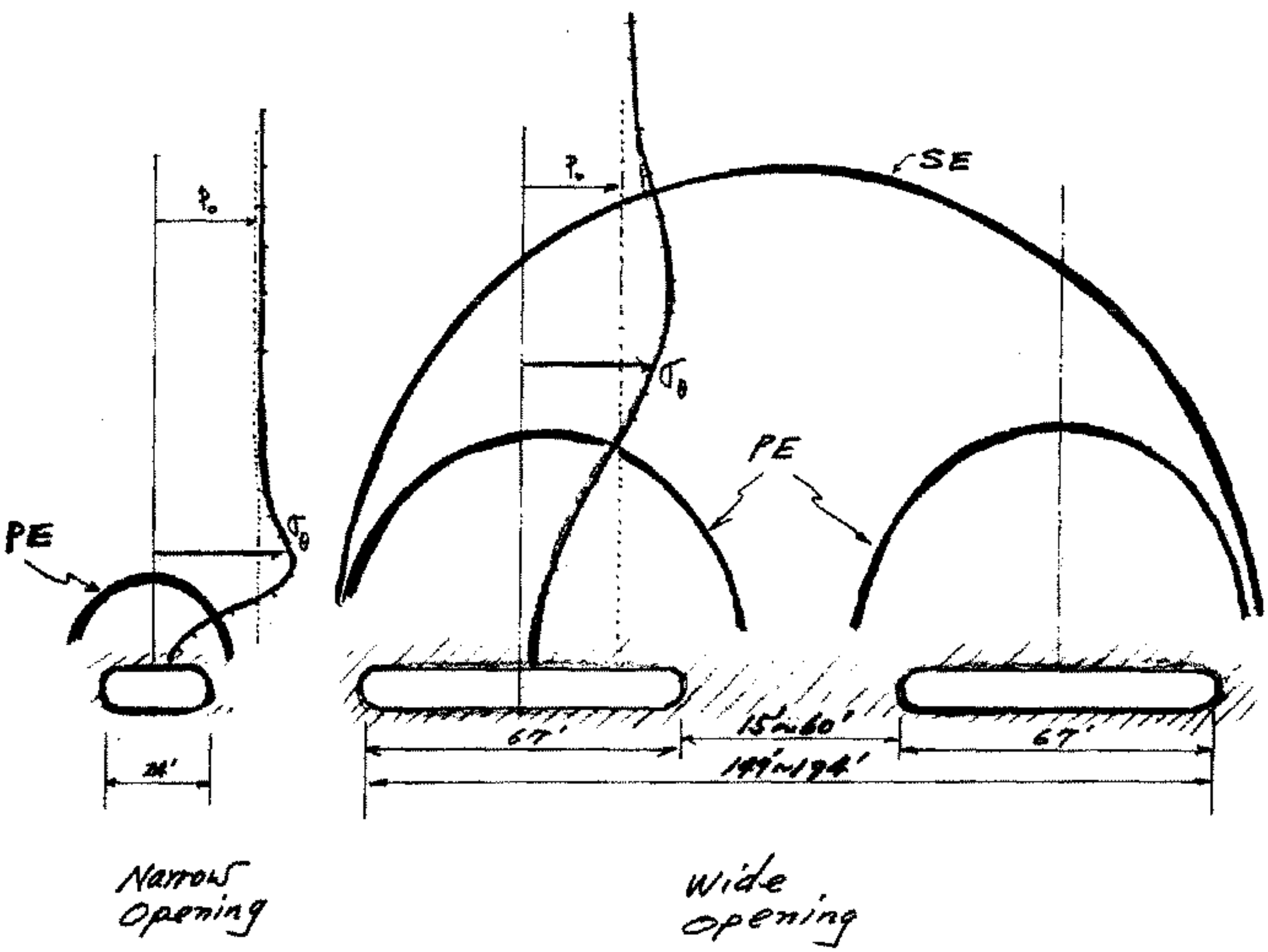

Figure 3. Roof Improvement by Increase of Room Width with Same Extraction Rate. ($\sigma\theta$) Tangential Stress in the Roof Media, (PE) Primary Stress Envelope, (SE) Secondary Stress Envelope.

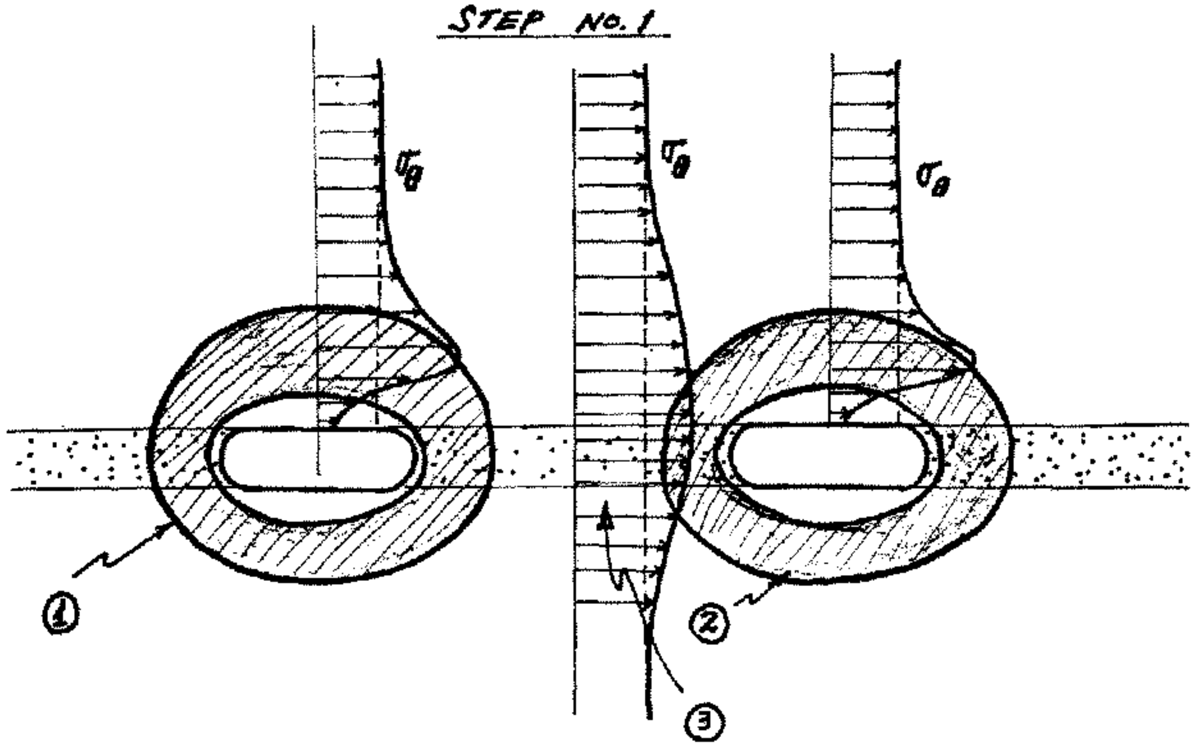

Figure 4. Prestress Loading in Stress Control Method. (1) Prestress Opening with Primary Stress Envelope, (2) Another Prestress Opening with Primary Stress Envelope, (3) Stress Increase and Strain Hardening (σθ) Tangential Stress Along the Centerline in Roof Formation.

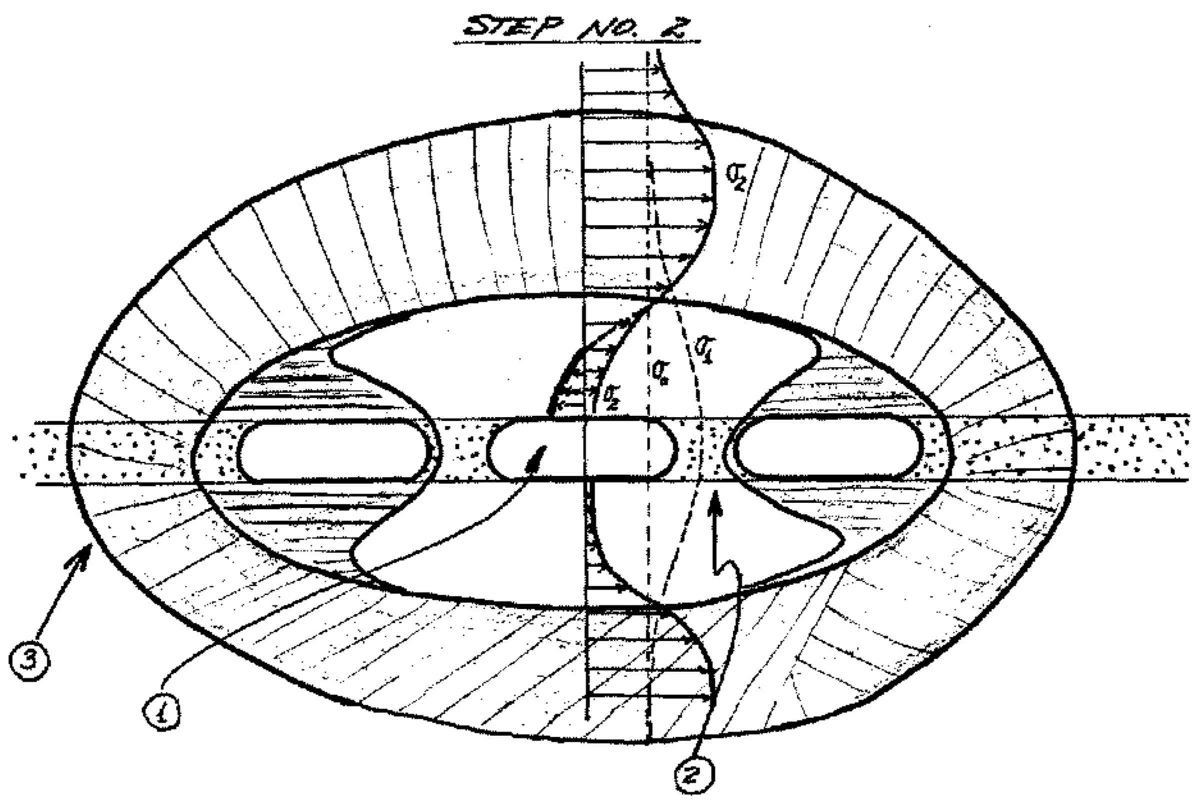

Figure 5. Formation of Protective Stress Envelope by Stress Control Method Using Three Basic Openings. (1) Excavation of Protected Room, (2) Formation of Yield Pillar, (3) Transformation into Single Protective Stress Envelope. (σθ) Initial Lateral Stress, (σ_1) Increased Lateral Stress after Preloading, (σ_2) Lateral Stress after Completion of Three Openings.

resultant stress envelope is formed in a particular shape and intensity so that it can withstand the anticipated increase of the earth pressure. Inside of the protective envelope lies a large mass of stabilized ground which acts as a protective lining. The protective zone is designed to absorb the future increase of the ground stress.

One of the most critical parts of this design is the time-dependent change of stress in the immediate roof around the protected room. The horizontal stress here should be controlled so that excess tension development does not occur. Otherwise a deep tension crack may develop along the centerline of the roof over the protected room. The size of the protective envelope should be determined so that there is no interaction of the stress envelope with weak strata over the roof.

The effectiveness of the Stress Control Method was proven by extensive insitu stress measurements using the Serata Stressmeter. The measurements reflect the change in the stress envelopes in relation to the geometric pattern and time sequence of excavation, predicted by the theory. More specifically, the speed of the stress distribution pattern is dictated by the tensor coefficients of the ground materials. In both yield and abutment pillars, the vertical stresses are always greater than the lateral stresses by an amount set by the octahedral shearing strength of the pillar material. Over the roofs of the openings, the critical lateral stresses change gradually with time, approaching a certain asymptote.

The effectiveness of the protective stress envelope is demonstrated in the substantial reduction of the creep closure rate in the protected room as shown in Figure 6. In one field case, without stress control, the closure rate taken at the room center was over 2,000 μ-in/hr. The closure rate taken at the same time across a stress controlled room was substantially smaller as compared in the creep distribution curves of the figure. The stability of the stress controlled room is noted in the following observations. (1) The roof relaxation creep rate is significantly reduced, (2) swelling at the room center is virtually eliminated, (3) room closure becomes almost the same as the deformation rate of the yield pillar, (4) the two prestress openings experience much less creep closure than the uncontrolled single room. In comparing these two tests sites which have greatly different extraction rates, you find one interesting lesson; that is, extraction rate is not necessarily a meaningful criterion for underground safety. The criterion should be the stress conditions of underground openings.

An even more interesting comparison between the two test entries was made when the internal creep rate distribution patterns of their roof media were examined, as shown in Figure 8. The data was taken by the Serata Electronic Microcreep Meter which is also shown in the figure. A number of probes of the Meter are self-anchored quickly in ordinary anchor bolt holes as shown in the diagram. The sharp peaks of the uncontrolled roof indicate clay separation with different velocities at various depths. The first clay seam at 2.5 ft. is separating at a rate up to 1,000 times faster in the uncontrolled roof compared to the controlled one. The scale of the creep rate is given in logarithms.

The effect of water to the roof formation of solution cavities is significant. The cavities created by the Stress Control Method were proven to be much more stable in water than those without control. For example, the mine layouts shown in Figure 7 were created for the purpose of comparison. After several months of observation, the whole mine was flooded by an accident. The mine openings were filled by brine with waterhead of 3,000 ft. for about a year and a half. When the floodwater was finally removed, all the roofs of the mines were found to have failed with one exception; that was the stress controlled area. It would seem logical that the stress controlled roof is less susceptible to the brine penetration because of the less separation in the immediate roof.

MULTI-STAGE STRESS CONTROL

One important requirement for success of the Stress Control Method is to avoid interference of the stress envelope with any weak geological formations commonly found above a bedded salt formation. This can be accomplished by regulating the total dimension of the final protective stress envelope. The dimension of the envelope and its height are determined by the total lateral dimension of the openings.

In both mining and solutioning, the width of individual openings may be restricted by two uncontrollable factors; namely, method of excavation and height of the salt bed. However, by creating a multiple of openings according to the principle of the Stress Control Method, the dimension of the final protective stress envelope can be controlled.

Such an example is shown in Figure 9. A total room width of 340–350 ft. was created in a bedded potash formation of 10 ft. thickness. The final protective stress envelope was formed by a combination of seven individual openings as illustrated in the figure. The three center openings were created after a set of two openings on both sides were excavated by the Stress Control Method. In this seven opening system, the separation of the weak formation at 30 ft. in the roof was significantly reduced. The actual underground layout of the seven opening system is shown in Figure 10.

STRESS DISTRIBUTION

Stress distribution in a rock salt formation has never been observed before because of the nonelastic nature of rock salt. All the existing stress measuring methods developed to date are based on an assumption of ideal elasticity which does not exist in rock salt. The Serata Stressmeter

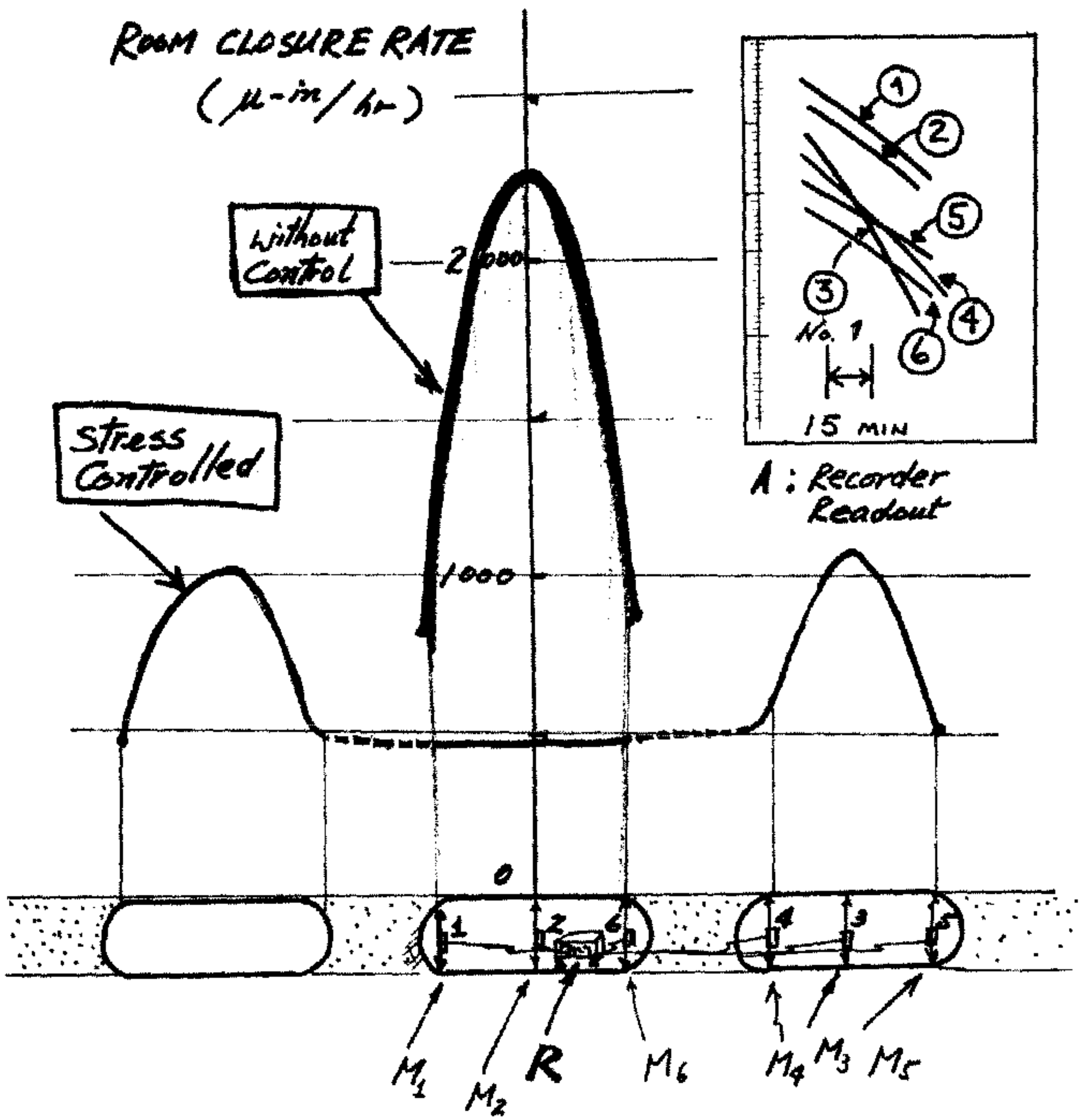

Figure 6. Comparison of Room Closure Rate Distribution Patterns between Single Room and 3-Room System demonstrating Effectiveness of Stress Control Method. (R) Serata Microcreep Meter, (M_1, M_2 . . . M_6) Six Probes of the Meter, (A) Recorder Readout, Readings Obtained in Approximately 45 min. for each Location.

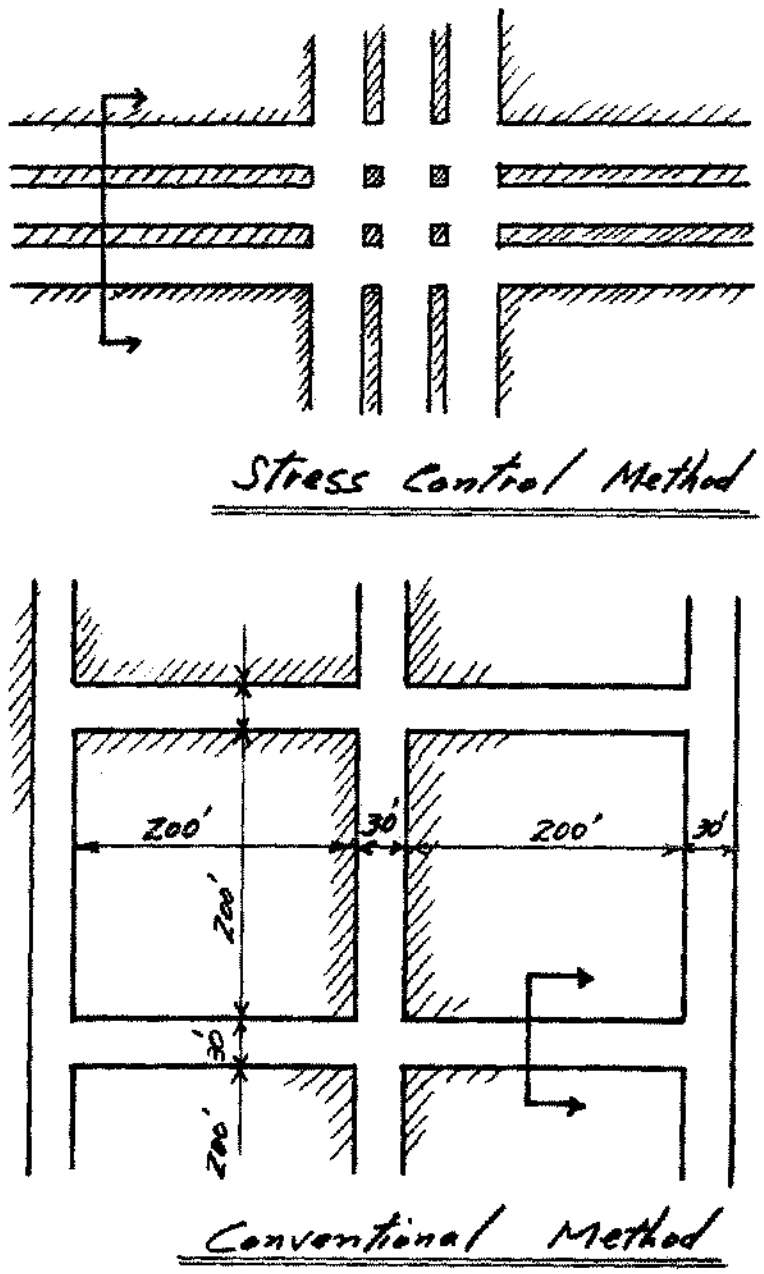

Figure 7. Layout of Stress Controlled Rooms Compared with Conventional Layout.

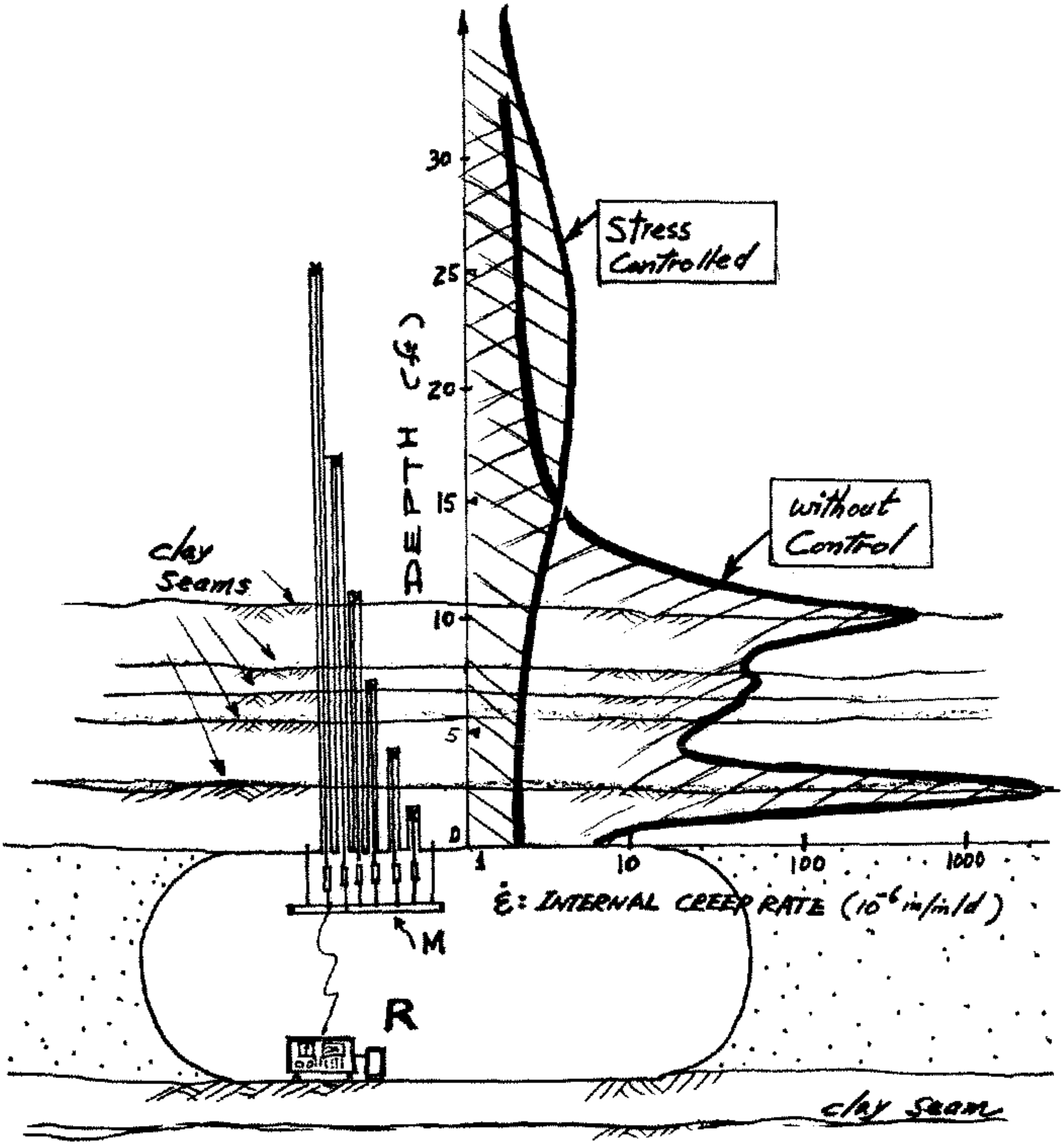

Figure 8. Comparison of Internal Creep Rate Distribution in Roof Formation over Two Different Types of Rooms, One Made by Stress Control Method and Other by Conventional Method. (R) Serata Microcreep Meter, (M) Six Probes of the Meter.

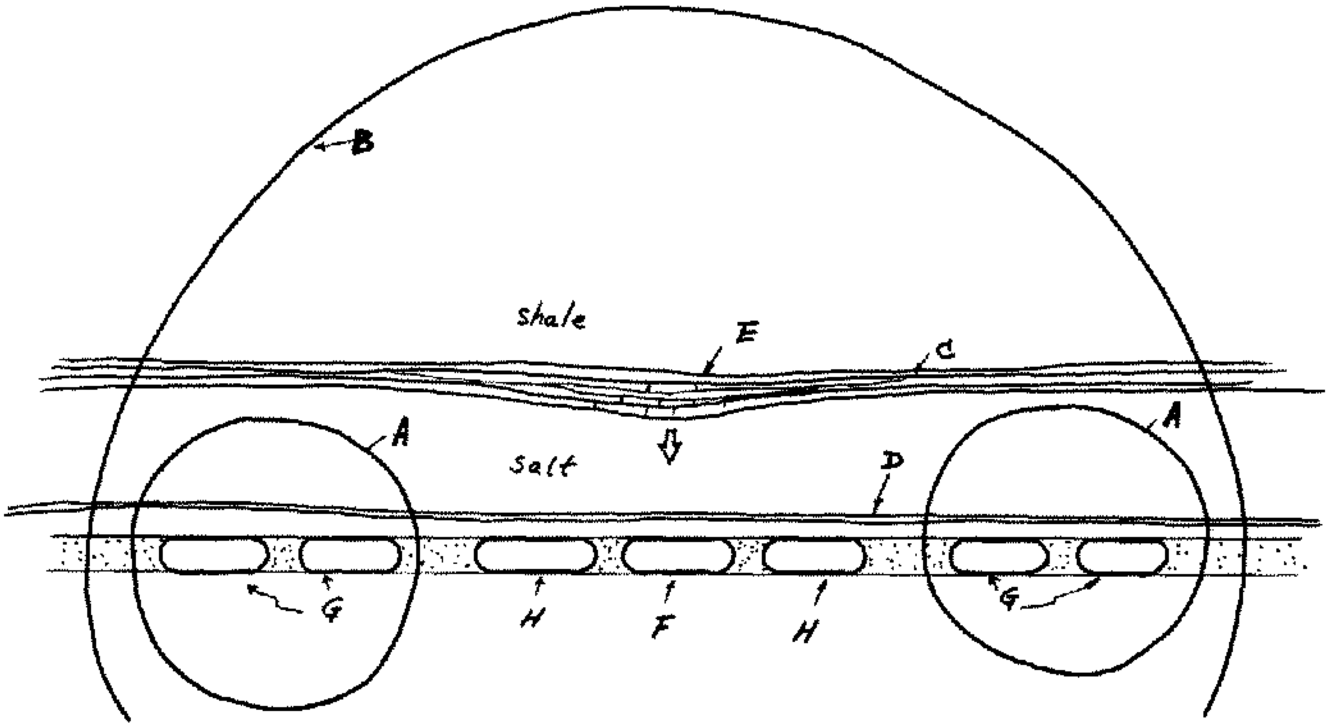

Figure 9. Multistage Stress Control Method for Elimination of Deep Separation. (A) Primary Stress Envelope, (B) Secondary Stress Envelope, (C) Deep Weakness Seams, (D) Shallow Weakness Seams, (E) Deep Separation, (F) Protected Room, (G) Initial Pre-stress Rooms, (H) Pre-stress Rooms.

can determine the stress in rock salt because it is based on the total properties of rock salt; namely, elasticity, visco-elasticity and visco-plasticity. The actual stresses detected in salt mines were found to be quite different from what might be expected from the textbook concept of stress distribution, as described below.

In yield pillars, a sharp rise of stresses is observed as shown in Figure 11. The shape and magnitude of the stress distribution pattern change drastically with the room width and time. A stabilizing yield pillar reduces the stress level while a failing one increases it. When the room width is increased, the stress plateau area starts to develop as shown in Figure 12.

A much greater stress level is found in the abutment of a multiple room entry as shown in Figure 13. In the figure, the stress level is found to be much smaller than the calculated value in an undisturbed area. The stress level gradually increases with an increase of areal extraction. This seems to indicate that the initial overburden load does not apply fully to the rooms during the initial development of an opening. It is the rigidity of the overlying formations that is partially supporting the overburden load. The full overburden load is gradually applied to the opening by the yielding of the overburden formations. The areal expansion of surrounding excavation accelerates this process of yielding.

ROOM WIDTH AND CONTROL

The field study of roof failures over underground openings may be summarized in the general relation of room width and safety period, as shown in Figure 14. Here, room width indicates the total width of one or more openings. Safety period is the time during which roof damage does not interfere with mining operations. Therefore, this value should be specific to individual ground conditions and the mining method employed. In this diagram, the safety period is used merely as a relative index showing the degree of roof stability.

With a relatively homogeneous salt above, the stability of the roof formation improves with an increase of the room width as indicated by Curve 1. Under the same extraction rate and overburden loading, increasing the room width would have a negative effect on safety if there were any shallow clay seams in the roof formation as illustrated by Curve 2. This is due to the quick separation of the seams. The separation may be eliminated by adopting the Stress Relief Method and the Stress Control

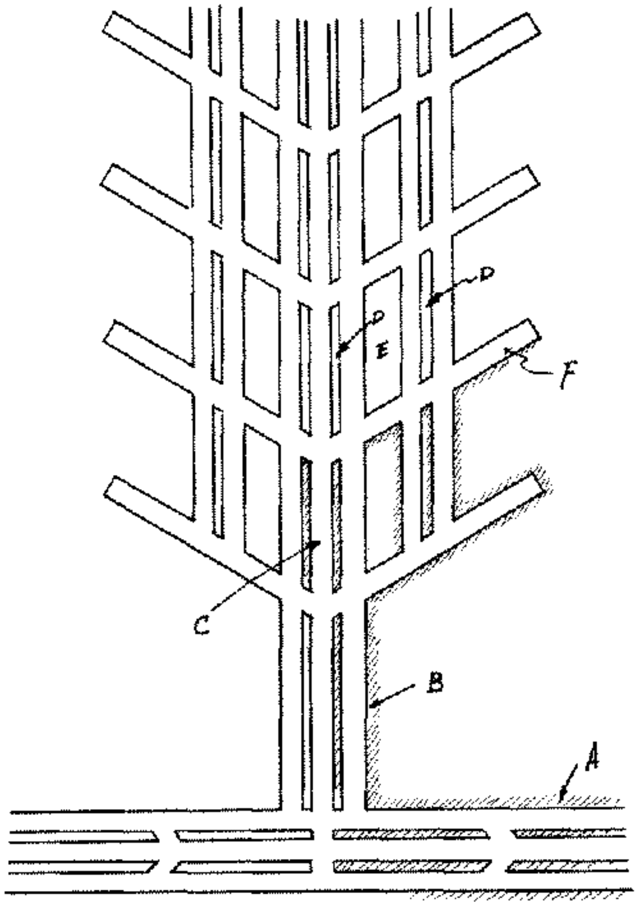

Figure 10. Basic Scheme of Potash Mine Production Panel Developed Using Concept of Multistage Stress Control Method. (A) Block Entry, (B) Panel Entry, (C) Belt Entry, (D) Yield Pillar, (E) Minor Abutment, (F) Production Breakthrough.

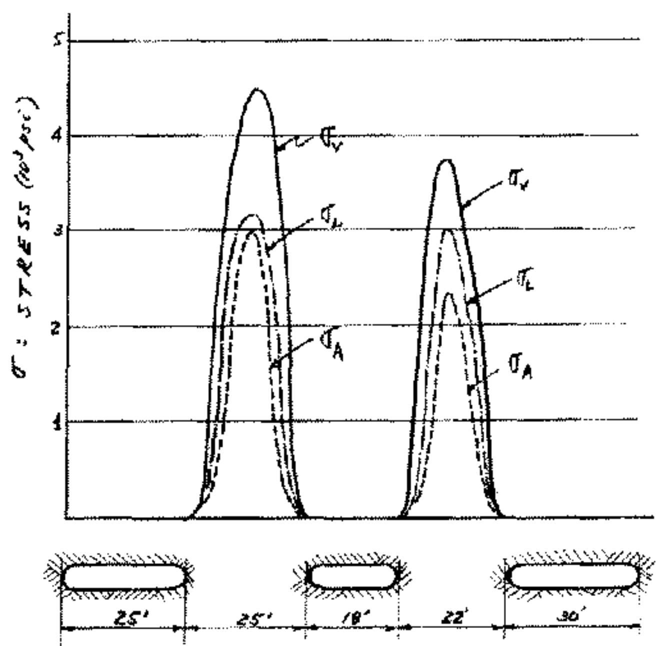

Figure 11. Stress Distribution Patterns in Narrow Yield Pillars. (σ_V) Vertical Stress, (σ_L) Lateral Stress, (σ_A) Axial Stress.

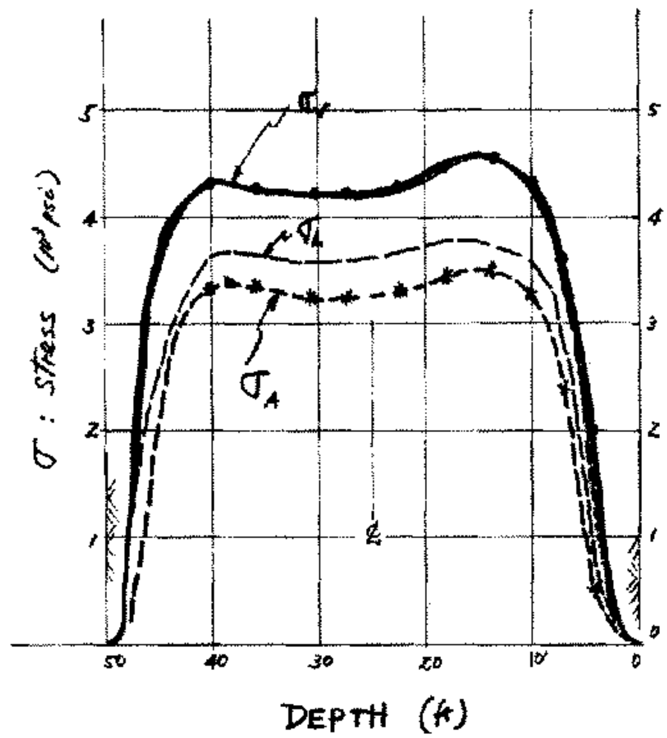

Figure 12. Stress Distribution Pattern in 50 ft. Wide Pillar under Overburden Pressure of 3100 psi. (σ_V) Vertical Stress, (σ_L) Lateral Stress, (σ_A) Axial Stress.

Method with two and three openings respectively as indicated by Curve 3.

The roof of the multiple rooms may fail whenever deep clay seams interfere with the stress envelope, also indicated by Curve 3. Under such a circumstance, the failure should be avoided by regulating the position of the stress envelope with the multiple stage stress control. Although the safety-width relationships will be different in individual underground conditions, the relation given in Figure 14 illustrates the basic scheme of controlling ground movement over solution cavities.

DESIGN EXAMPLES

The roof control technique was successfully utilized for designing a brine field in a salt bed located in the State of New York at the depth of 1,400 ft. Two solution cavities 300 ft. in diameter were placed in the salt bed of 50–55 ft. thickness. Between the two cavities, a yield pillar of 100 ft. was maintained. A protective envelope was formed outside of the 360 ft. thick weak shale formation overlying the salt bed as shown in Figure 15. One cavity alone would not be able to provide a stable roof because of the size of the primary stress envelope which is formed within the weak shale formation as illustrated in the same figure. Only by combining the primary stress envelopes with the small yield pillar, the final protective stress envelope can be placed in the competent limestone overlying the shale formations.

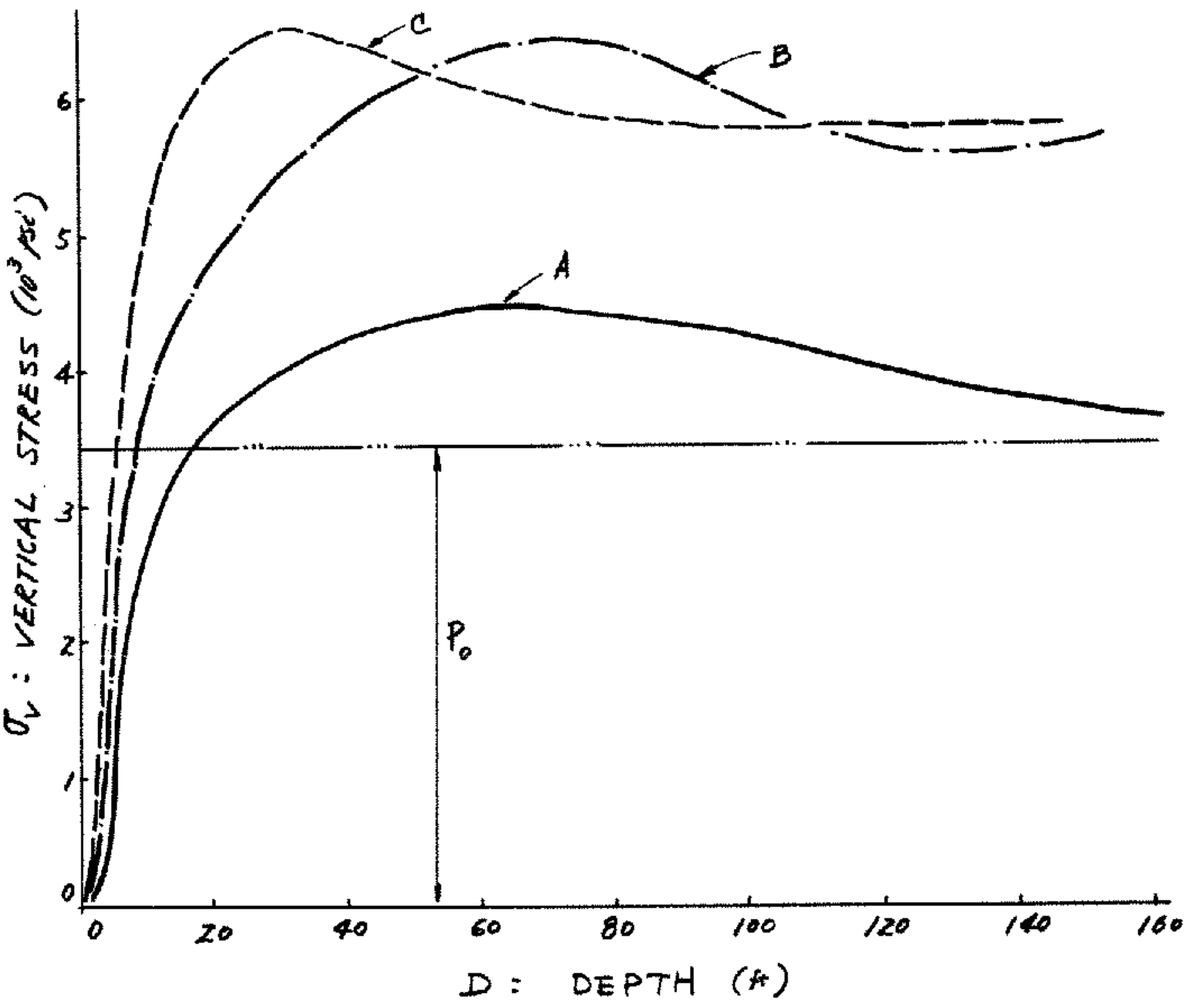

Figure 13. Comparison of Stress Distribution Patterns in Abutment Pillars with Different Surrounding Extraction Schemes under Same Loading Conditions. (A) 200 ft. Wide Interpanel Abutment Pillar, (B) Abutment in Highly Loaded Area, (C) Abutment in Undisturbed Area, (P_o) Overburden Pressure.

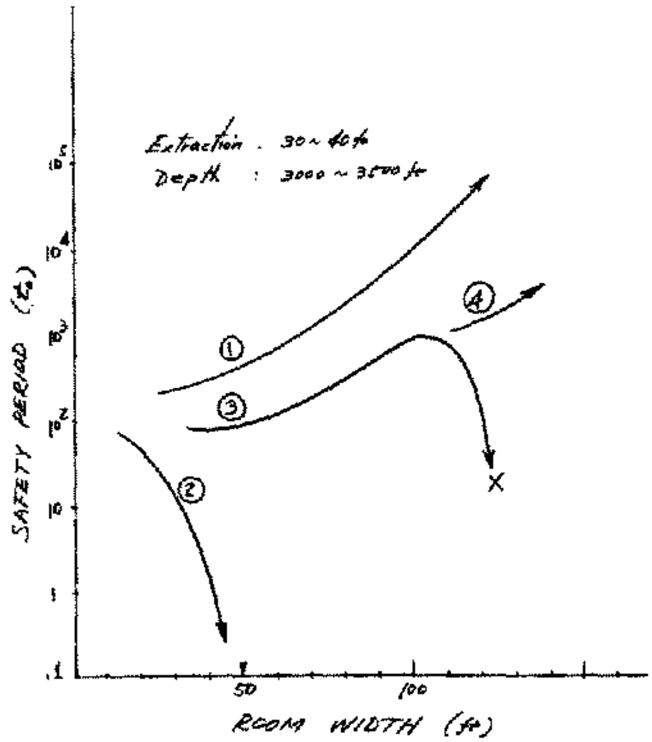

Figure 14. Roof Control Techniques Related to Room Width and Safety Period of Openings. (1) Homogeneous Salt, (2) Failure by Shallow Clay Seams, (3) Stress Control, (4) Multistage Stress Control, (X) Failure by Deep Seam Separation.

The pattern of the stress change taking place in the roof formation is also shown in Figure 15. The sharp stress gradient inherent to the single cavity is replaced by the final stress distribution in which both the stress gradient and magnitude of the critical stress are substantially reduced in the critical formation immediately above the exposed roof. In order to facilitate this stress relief method, it is important to follow a certain procedure of solutioning. First of all, the two cavities should be started at nearly the same time. In the individual cavities, the solutioning should be started at the bottom and gradually dissolved upward.

During the last three year period, the safe operation of the brine field with the double cavities has been maintained without any reported roof failures. Movement of the surface has been monitored over the years with no measurable surface subsidence with the instrument accuracy of 0.020 inch. The surface subsidence observation will be continued to assure the stability of the multicavity system.

If control by two cavities is not adequate, a three-cavity system may be adopted equally well as illustrated in Figure 16. In this case it is desirable to have a certain time difference between the start of solutioning, the outside cavities and the center cavity. The manner of solutioning in the individual cavities should be identical to the case of a two-cavity system. Since the critical roof support should

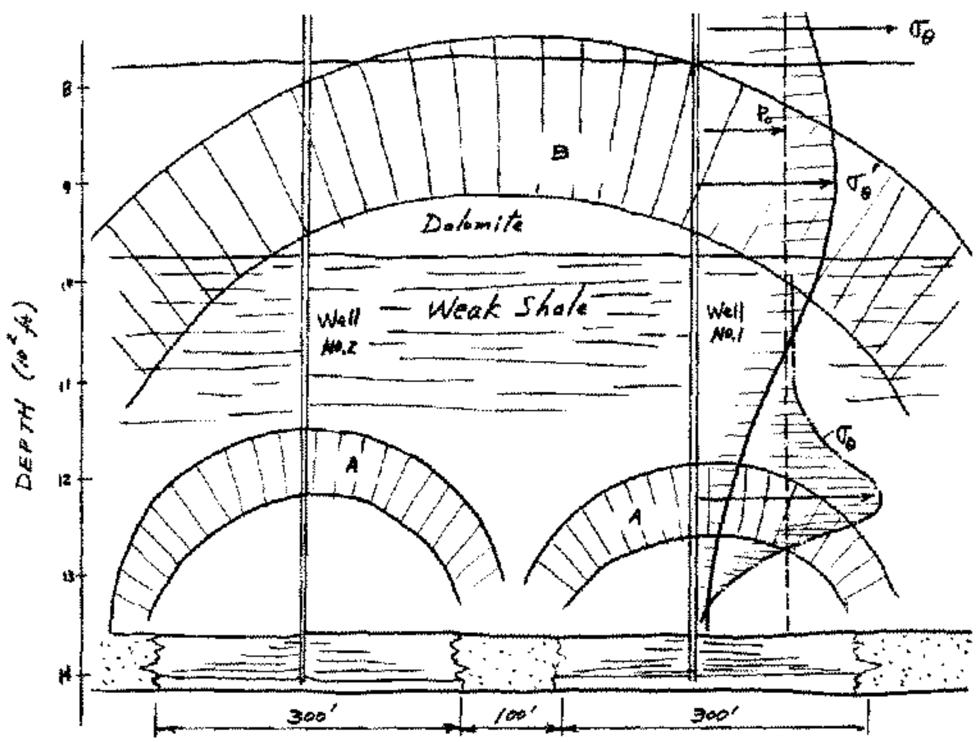

Figure 15. Example of Stress Relief Method Applied for Design of Solution Cavities in State of New York (a) Primary Stress Envelope, (B) Protective Secondary Stress Envelope, (P_o) Overburden Load, ($\sigma\theta$) Tangential Stress by Primary Stress Envelope, ($\sigma\theta'$) Tangential Stress by Secondary Stress Envelope.

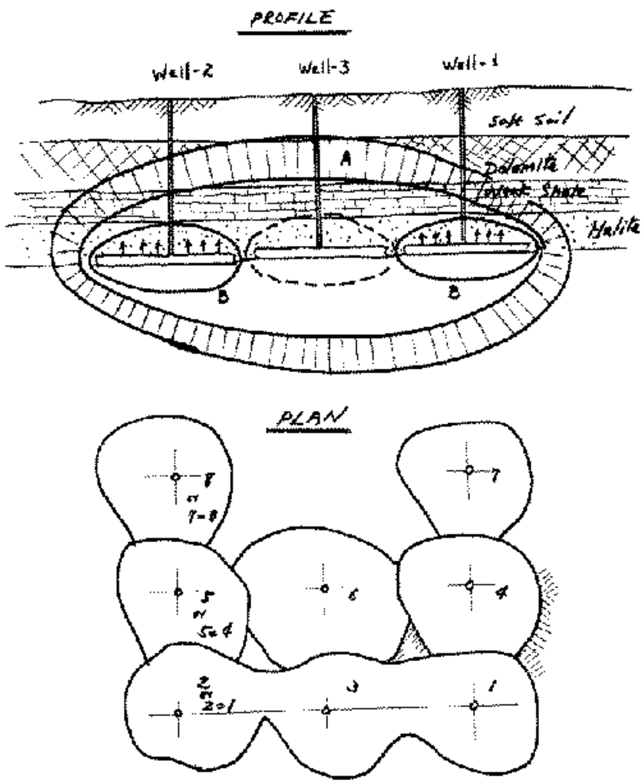

Figure 16. Stress Control Method Applied for Design of Solution Cavities in Bedded Salt Formations with Overlying Weak Shale, *Profile:* (A) Protective Secondary Stress Envelope, (B) Primary Stress Envelope, *Plan:* Sequence in which Solution Cavities Were Developed.

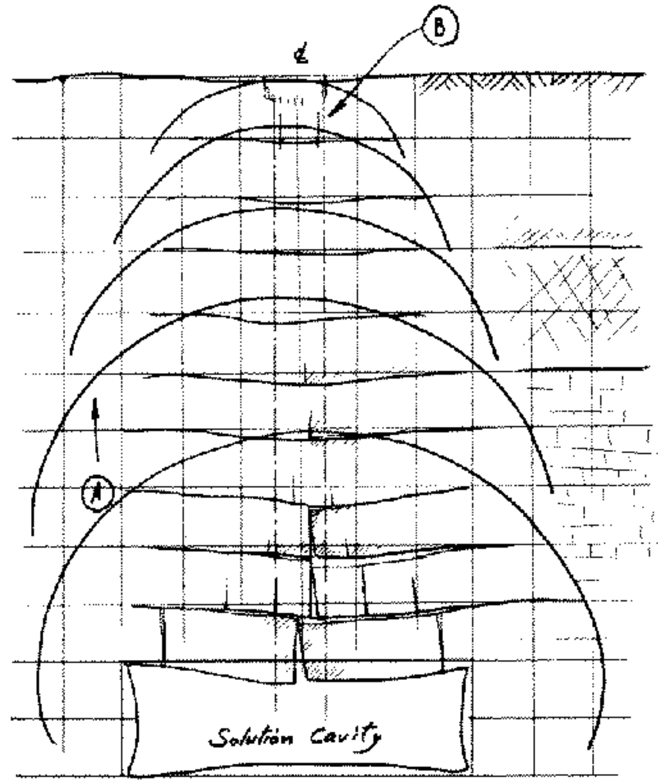

Figure 17. Mechanism of Sinkhole Development Based on Underground Stress Measurement and Theory of Viscoplastic-Brittle Behavior of Overburden Formations. (A) Stress Envelope Rising Upwards Caused by Time-dependent Brittle Failure, (B) Chimney Concept of Sinkhole Development.

be provided in the direction of the line connecting the three cavities, the extension of the brine field in the direction perpendicular to the line can be accomplished without seriously weakening the roof formation. This development is illustrated also in Figure 16. The order of solutioning should follow a certain time sequence as indicated by the numbers from 1 to 8 in the figure.

SINK HOLE DEVELOPMENT

Sink hole development is not unusual over a solution cavity or cavities. The mechanism of sink hole development is viewed by soil engineers as a sequential roof fall forming a vertical hole or so-called chimney as shown in Figure 17. This idea has been formed mainly from their visual inspection of the surface hole without any underground stress measurements.

An entirely different interpretation of sink hole development can be made when it is observed from the underground by measuring the actual stress change around open cavities. This view of sink hole development from the underground is shown also in Figure 17, which compares it with the view of conventional soil engineers. As illustrated in the figure, an extensive stress change is taking place before the initiation of roof failure, particularly over a solution cavity. This is due to the viscoplastic deformation of the salt and shale formations surrounding the cavity. The sink hole development on the surface is a result of the rising stress envelope reaching the surface or the soft ground near the surface, where there is no strength to provide support to the growing stress envelope. This lack of support results in a sink hole at the surface.

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METRIC CONVERSION

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