Pressure-Temperature Effect on Spherical Cavities in Massive Salt

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ABSTRACT

Laboratory experiments were conducted on miniature cavities in five-inch diameter by six-inch long salt cores under a triaxial stress condition of 3,000 psi and a temperature of 130° F. The effects of tri-axial compression and creep were observed. Further, a limited study of thin sections was conducted to determine the relationship between the movement of the salt and the patterns of microfractures and cracks.

The experimental results indicated that the closure, or decrease in volume, for an empty spherical cavity within a salt dome at 3,000 psi and 130°F is in the range of 2.5% to 3.0% of the initial volume.

I. INTRODUCTION

This investigation was initiated as a part of a project grant from the United States Atomic Energy Commission to the Petroleum Engineering Department of The University of Texas. The program of research involved several areas, among which was the problem of determining structural stability of certain, well-defined, cavity shapes. In order to determine if a large cavity could be constructed and readied in the selected salt medium, a feasibility study was authorized in which the theoretical approach to the stability problem was augmented by test data on cores obtained from the region selected for a future test.

Purpose and Scope of this Investigation

The purpose of this investigation was to determine the effect of overburden pressure and temperature on a spherical cavity in a salt dome. Model cavities in salt cores were subjected to stress and temperature conditions found at 3,000 feet of depth. Cavity deformation was observed. A limited investigation of the movement of salt was conducted by microscopic examination of various thin sections.

The spherical cavity was chosen for experimental study since a theoretical solution to the stability problem of such cavities has been presented (1). This particular cavity shape, allowing for slight irregularities may be attained with rather good success by solution mining methods, using specially developed techniques (2).

Previous Investigations

The problem of accurately determining the stresses which exist in rocks in the earth's crust is indeed a complex one. Theoretical studies have differed widely in many of the basic

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assumptions about the physical properties of the rock itself. Some solutions of problems in underground stress analysis assume that rock is elastic, homogeneous, and isotropic in character; others assume that rock possesses plastic, viscous, elastico-viscous properties, or a combination thereof. Experimental evidence has shown that salt possesses plastic, viscous, and elastico-viscous properties (3).

II. APPARATUS AND PROCEDURE

To approximate overburden conditions as closely as possible, testing equipment was designed to simulate triaxial stress conditions without resorting to the application of fluid pressure directly on the salt mass. The equipment consisted of a base plate, test cylinder, and piston shown in Fig. 1. The diameter of the test cylinder made from an AISI Type 347 stainless steel alloy which offered high strength at relatively high temperatures was five inches I.D. The piston and the base plate were machined to fit the test cylinder. Lateral pressure was verified effective on the salt core by strain gage measurements on the outside of the steel cylinder (4). Load was applied to the core by placing the assembled test cylinder in an Olsen testing machine capable of producing a 100,000 pound load.

Cores, as received, were between 5-3/4 inches and 6-1/4 inches in length. Those with nonparallel ends were cut with a diamond saw to insure that the ends were perpendicular to the axis of the core. This procedure decreased the length by no more than 1/4 inch. All cores had a diameter of 4-15/16 inches, i.e., 1/16 inch smaller than the inside diameter of the test cylinder.

Seven different experiments were attempted to determine the pressure-temperature effects on model cavities in the salt cores.

Figure 1. Base Plate, Cylinder, and Piston Disassembled.

Procedure for Preparing and Testing Cores

The stepwise procedure for the preparation of the first two cores was as follows:

1. A 5/8-inch hole was drilled 3-15/16 inches into the core with a steel bit and high speed hand drill. The hole was centered in the core by holding the core in the test cylinder and guiding the drill bit with a steel template centered on the steel cylinder.
2. A 1-3/4-inch diameter sphere was then cut in the center of the core by inserting into the 5/8-inch hole a tool especially designed and built for this purpose. When the cap plate of the cutting tool (Fig. 2-no. 1) was seated on the top of the salt core there was about 1/32-inch clearance at the bottom of the 1/2-inch diameter cutter shaft (Fig. 2-no. 2). This made it possible to start cutting the cavity at the bottom of the hole, and the very slight clearance prevented the shaft from jamming. The tool was mounted on the core by means of a C-clamp. The hex stock (Fig. 2-no. 3) was turned with finger pressure until the cutter blade (Fig. 2-no. 4) contacted the salt. The ratchet handle (Fig. 2-no. 5) was turned until the cutter blade rotated freely at which time the cut was complete. The follower screw (Fig. 2-no. 6) was advanced so that it fitted snugly against the top of the hex stock at all times. This provided stability for the cutter shaft and was necessary since the shaft bearing in the cap plate was narrow. After four or five cuts, the tool was removed and the cuttings emptied from the cavity. The above procedure was repeated until the cutter had been rotated through ninety degrees.

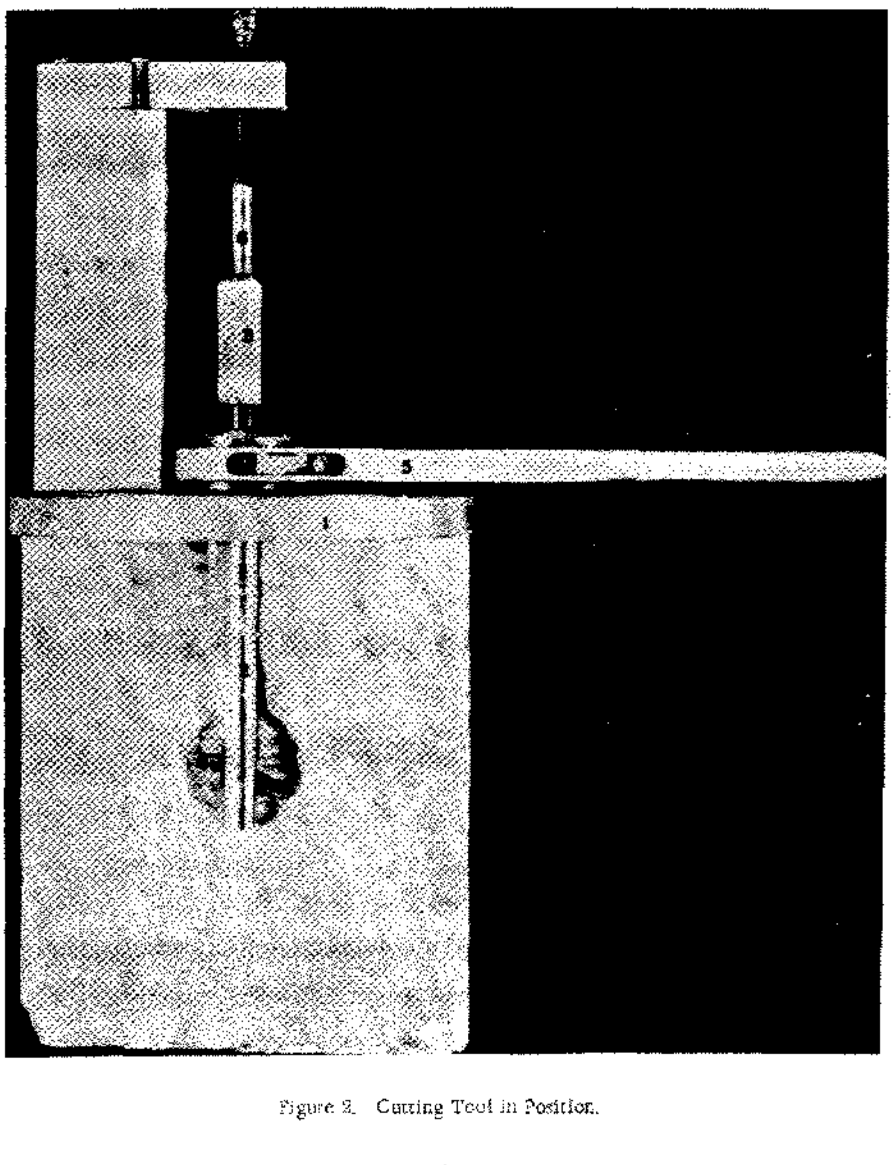


Figure 2. Cutting Tool in Position.

Although the cutting of a spherical cavity became tedious and time-consuming, a symmetrical and sufficiently smooth-walled cavity could be obtained.

3. After cutting the spherical cavity, a 3/4-inch O.D. by 5/8-inch I.D. steel pipe seven inches long had to be centered and cemented in the core to provide an outlet. First a 2-1/4-inch hole was cut with a hole saw and milled with a 5/8-inch steel bit through the top of the core to form a shoulder within 1/4 inch of the top of the cavity. The drilling and milling was done with a drill press.

4. The entire outer surface of the core was then coated with a thin film of epoxy resin. This coating was to prevent any water in the cement slurry used to cement the core into the test cylinder from entering the cavity through permeable features which might have been present in the salt core.

5. A stainless steel packer (2-1/4-inch O.D. × 1/4 inch thick with a 3/4-inch I.D. centered hole) and the steel pipe (3/4-inch O.D. × 5/8-inch I.D. hereafter referred to as casing) was then cemented in place on top of the cavity with Sauereisen ceramic cement. See Fig. 3. Extremely close tolerances required the casing to be centered exactly. Again the core was held in the test cylinder with the casing centered by a steel template while the packer-casing assembly was cemented in place.

6. The initial volume of the spherical cavity was determined at this point by filling the cavity with mercury to the top of the casing. By subtracting the volume of the inside of the casing, the initial volume of the cavity was ascertained.

7. At this point the core assembly was ready to be placed in the test cylinder. First, all parts of the base plate, cylinder, and piston that were to be in contact with the salt were coated with a thin film of paraffin by brushing on a solution of paraffin and kerosene. This served three purposes: (a) it protected the metal surfaces from corrosion, (b) it prevented the cement from adhering to the metal, and (c) it facilitated removal of the core

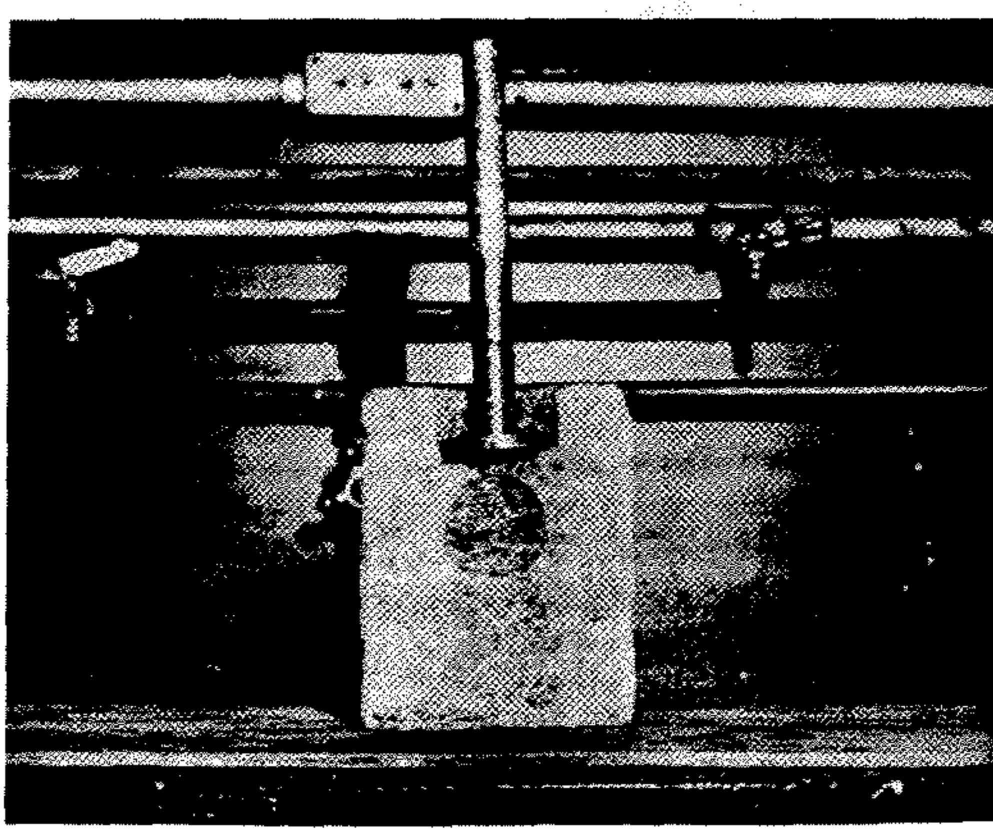


Figure 3. Sample Core with Casing and Packer in place before being Cemented.

from the test cylinder. Next, with the test cylinder positioned on top of the base plate a salt-saturated cement slurry was poured into the bottom of the empty test cylinder. The core assembly was then inserted into the test cylinder and rotated back and forth with downward pressure until the slurry oozed past the core and appeared at the top. Four grooves, 1/16 inch wide × 1/16 inch deep, equally spaced were cut parallel to the axis of the core to facilitate passage of the slurry from the bottom to the top of the core. This procedure allowed cement to fill any irregularities of the core surface. Then enough additional slurry was poured on top of the core to allow the casing to protrude approximately 1/2 inch past the top of the piston after it was placed on top of the core. Ample time was allowed for the cement to set, after which the entire test cylinder assembly was placed into the testing machine.

8. The heating elements and thermocouples were installed at this time. Two Ceramo thermocouples with ceramic insulation and enclosed in a 1/16-inch diameter stainless steel sheath were used; one was inserted 1-3/4 inches in the bottom of the base plate and the other 1-3/4 inches in the side of the test cylinder. Both were within 1/4 inch of the salt core. Heat was supplied by three 750 watt Chromalox strip heaters which were fitted around the outside of the cylinder. Voltage was controlled by a Fenwall thermoregulator and relay system. The entire cylinder-heating element assembly was insulated by placing a 13-inch I. D. metal sheath around the system and packing it with rock wool insulation. This allowed a thickness of two inches of insulating material around the circumference of the system.

9. A 50 ml. burette was connected to the casing by a 1/2-inch O. D. pipe. Mercury was poured into the burette until the cavity, casing, and pipe were full with the mercury level visible in the burette. Cavity volume changes were indicated by the burette reading.

10. The heating elements were then turned on and the temperature allowed to stabilize around 130°F for a sufficient length of time to insure uniform heating of the core.

11. At this point pressure was applied by increasing the load in equal increments with the testing machine until the maximum load, or stress, was reached.

    For the first two days temperature, load, and volume displacement readings were taken hourly, and as the rate of deformation decreased, readings were taken less frequently, perhaps once or twice a day. After a month or so, readings were necessary only once every two to three days. Upon recording the decrease in volume, which was generally accompanied by a decrease in psi loading, the total load was increased so as to maintain a substantially constant pressure on the salt cavity. This was necessary because as the plastic zone, or shell in a plastic state began to form around the cavity, the salt would relax and the load was relieved. As the test progressed and the rate of deformation decreased, such incremental increases in total load became smaller and smaller.

12. Upon completion of the test it was desirable to remove the core intact so that visual observations could be made. This was accomplished by first removing the base plate and piston. This left the test cylinder open at both ends. The core was then pressed out the bottom of the cylinder with a short section of 4-1/2-inch O. D. pipe by applying pressure with the testing machine. This required a load of 20, 000 to 30, 000 pounds which was equivalent to a shear stress of 170 to 250 psi at the boundary between the core and the test cylinder. The shear strength of the salt at zero normal stress was in the range of 800 to 900 psi (5), and the shear strength of the cement used was approximately 200 psi. Therefore, as the core was pressed out, movement occurred along the thin layer of cement between the test cylinder and the salt core.

13. After removal, each core was cut vertically in half and examined. Also, thin sections were prepared and examined from selected cores.

After the first two tests, several refinements were found desirable in preparing and testing the cores. These were as follows: (a) a greater mass of salt around the cavity and elimination of the packer-casing assembly were found desirable in order to reduce the interference of the movement of the salt, (b) a more accurate measurement of initial cavity volume, (c) a means of measuring the temperature in the center of the cavity to determine the temperature gradient throughout the salt mass, (d) a more precise volume measuring system to determine minute changes in cavity volume especially during the latter stages of creep, (e) a method for calipering the original cavity shape and dimensions before and after deformation, (f) measurement of the vertical movement of the salt core.

The size of the cavity was reduced to 1-1/4-inch diameter and a smaller diameter (3/8-inch O.D.), one-piece casing eight inches long replaced the packer-casing assembly. See Fig. 4.

This smaller size cavity was cut with much greater ease than the 1-3/4-inch cavities cut previously. Cementing of the casing was accomplished by first filling only the spherical cavity with mercury and then filling the 7/16-inch hole with salt-saturated cement slurry. With the slurry floating on the mercury, the 3/8-inch casing was inserted to the proper depth. Cement was prevented from entering the inside of the casing by placing a retrievable rubber plug in the bottom end of the casing. The plug was removed before the cement set. This method eliminated the shoulder and packer over the cavity and proved to be very successful.

The initial volume of the cavity was determined by first evacuating the cavity and casing with a vacuum pump to remove all air and then filling them with mercury. The mercury was then removed (by applying vacuum to the cavity), collected, and weighed. This procedure was repeated several times and an average value obtained for which the maximum variation was ±0.1 cc or an accuracy of 0.5%.

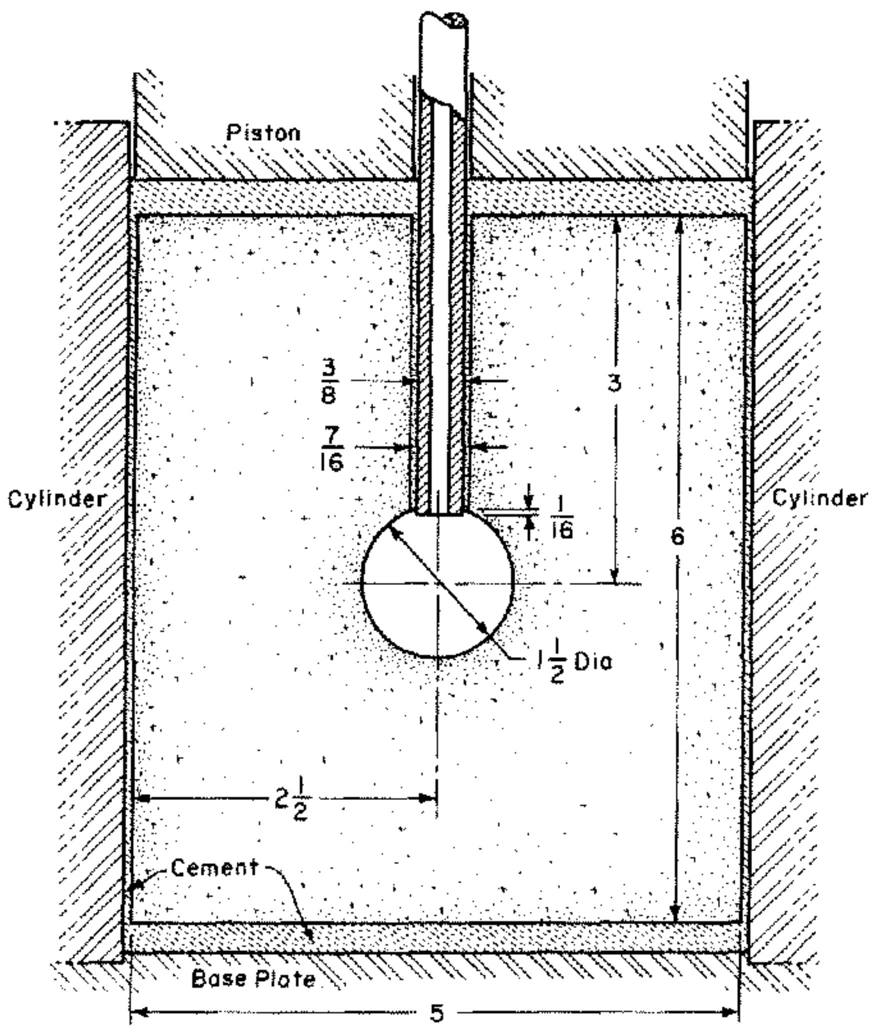


Figure 4. Proposed Assembly for Testing of Core No. 2.

Installation of a third Ceramo thermocouple accurately established the temperature in the center of the cavity. See Fig. 5. The thermocouple leads were inserted through a 1/16-inch hole in the casing head and down through the center of the casing. A drop of epoxy resin provided a seal around the stainless steel sheath.

The 50 ml. burette was replaced by a measuring device, built from two stopcocks and a small bore, 1/16 ml. pipette graduated to 0.001 ml. An accurate record of the temperature of the mercury was kept each time a reading was taken, and by applying the proper corrections all variations due to temperature changes were taken into consideration and changes in cavity volume were measurable within 0.001 cc, whereas previously the accuracy was limited to 0.05 cc.

This device was attached to the casing with a piece of 1/4-inch O.D., stainless steel, high pressure tubing which replaced the 1/2-inch O.D. pipe used before.

X-ray photographs of the salt cores provided an outline of cavity shape and dimensions before and after deformation. This method proved very useful in observing deformation. Pictures also showed the casing cemented in place and would expose faulty cement jobs. None was found.

A dial gage was installed to measure the downward movement of the piston in the test cylinder. Before loading the core to the maximum stress, a small load (about 5 to 10 psi) was applied, and the dial gage installed. Load was then applied in equal increments until the maximum stress was reached.

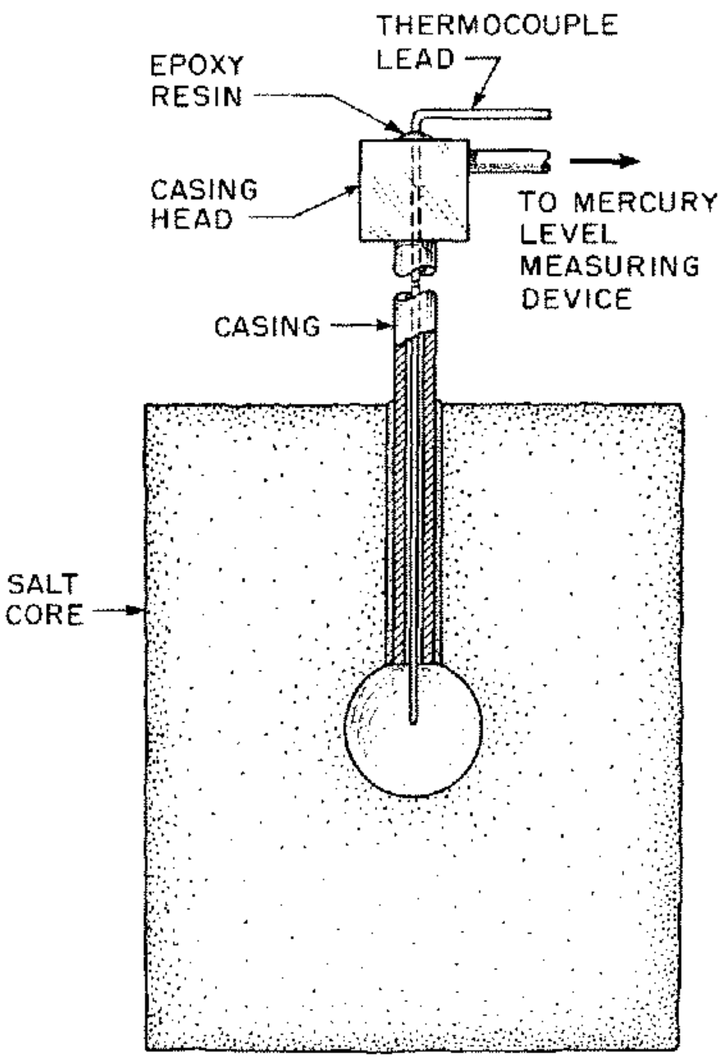


Figure 5. Thermocouple in Center of Cavity.

Figure 5 (a) shows the assembled test cylinder with the insulation and dial gage removed. Note [1] the three thermocouple leads, [2] the three strip heaters, [3] the thermoregulator, and [4] the measuring device in place. Figure 6 shows [1] the potentiometer, [2] the reference junction, and [3] the junction box, all used for thermocouple measurements. Shown also are [4] the temperature control relay, and [5] the switch box used to control the power supplied to the heaters.

III. PROCEDURE AND RESULTS

Experiment No. 1

This test was to determine the amount and rate of creep, and the time necessary for a spherical cavity to reach structural stability at a temperature of 130°F and a pressure of 3,000 psi. If the cavity exhibited structural stability at 130°F and 3,000 psi, then the load on the core was to be increased to 4,000 psi and the same observations made.

After loading the core into the test cylinder, the temperature was allowed to stabilize at 130 ± 2°F. After about two hours the system began leaking mercury. No pressure had been applied to the core. The experiment was abandoned and the core removed to try to determine the source of the leak. An unsatisfactory cement job around the packer-casing assembly and around the core itself was found to be responsible. No results were obtained from this first attempt.

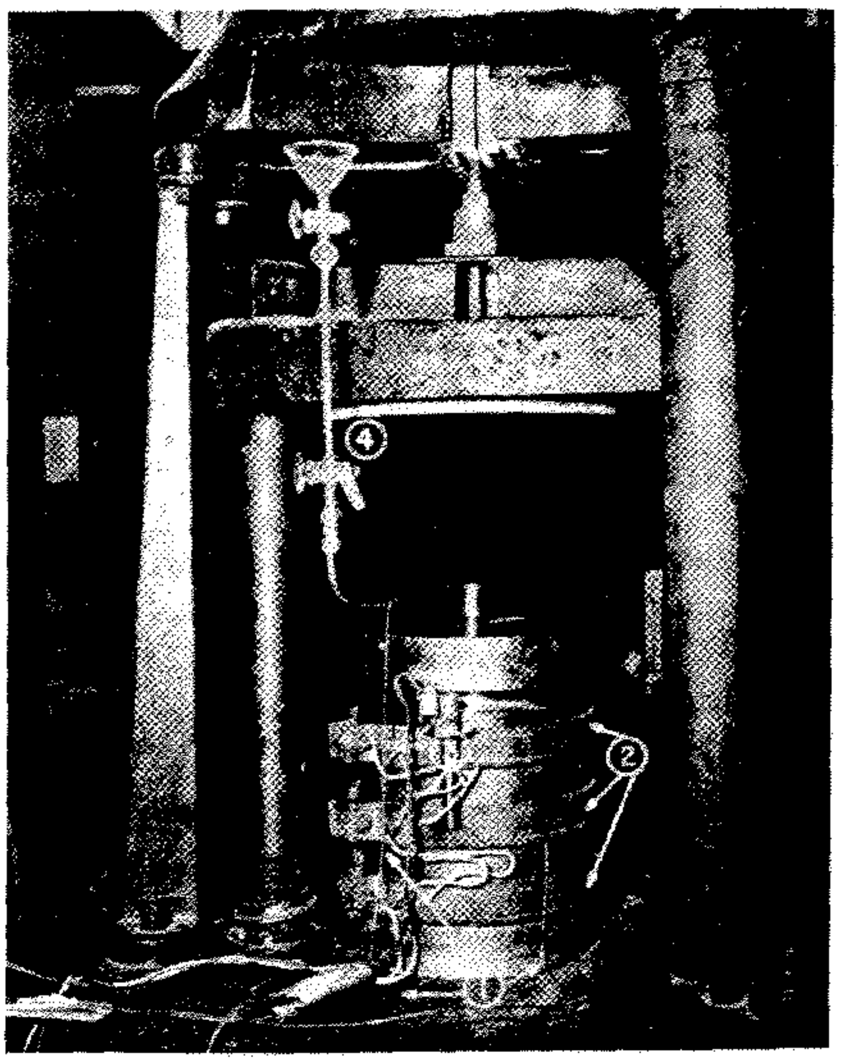


Figure 5 (a). Assembled Test Cylinder in Testing Machine.

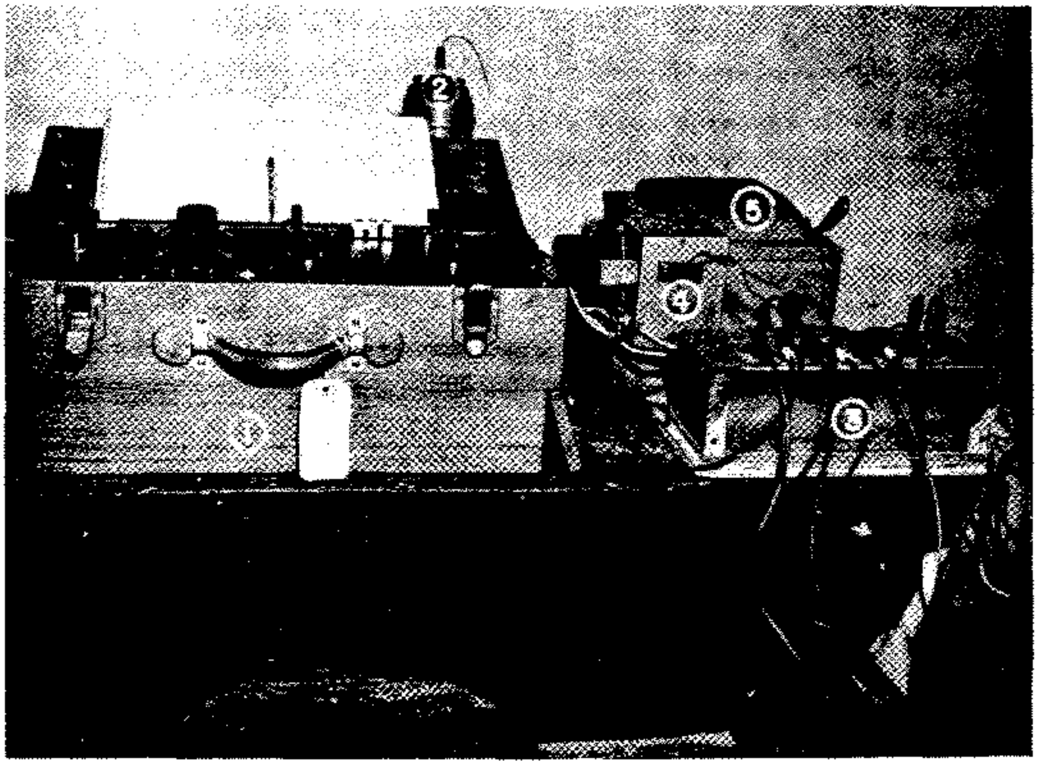


Figure 6. Temperature Control and Measuring Equipment.

Experiment No. 2

Fresh cement was used in preparing Core No. 2 and this apparently solved the cementing problem. After allowing the temperature to stabilize at 130 ± 2°F, load was applied to the core in equal increments of 600 psi every five minutes. In 25 minutes the maximum load of 3,000 psi was reached. This pressure was maintained for the next 90 hours. After the maximum loading, the cavity volume had decreased 0.6 cc, or approximately 1.1% of the initial volume. During the following period of 90 hours, no further decrease in cavity volume was observed. The pressure was then increased to 4,000 psi and was held constant at this value for a period of 85 days. The test was terminated at this time and the core removed from the test cylinder. Figure 7 shows the core after it was removed from the test cylinder. The horizontal fracture was caused during removal. The darker layers on the top and bottom of the core are cement used to eliminate any variation in pressure caused by nonparallel ends of the core. The thin layer of cement covering the external surface of the core shows the extent of the thickness of the section between the core and steel cylinder. The casing is shown cemented in place. Figure 8 shows Core No. 2 cut in half. It can be seen here that the horizontal fracture caused during removal of the core occurred at the packer. A slight, uniform deformation was noticed in the top half of the cavity as it appeared flattened. The white material shown inside the right half of the cavity is ceramic cement that must have leaked past the packer as it was being cemented in place. This volume of cement was measured and accounted for in computing the original volume of the cavity.

During the 85-day period, the cavity volume was reduced 4.1 cc representing a closure of 7.45%. Figure 9 is a plot of cavity volume decrease versus time. The shape of the curve indicated that the rate of closure was decreasing as structural stability was being reached, though complete stability was not obtained after 85 days.

Experiment No. 3

The purpose of this test was to study effects of slower rates of initial loading on the amount and rate of creep, and the time necessary to reach structural stability at approximately 130 ± 2°F

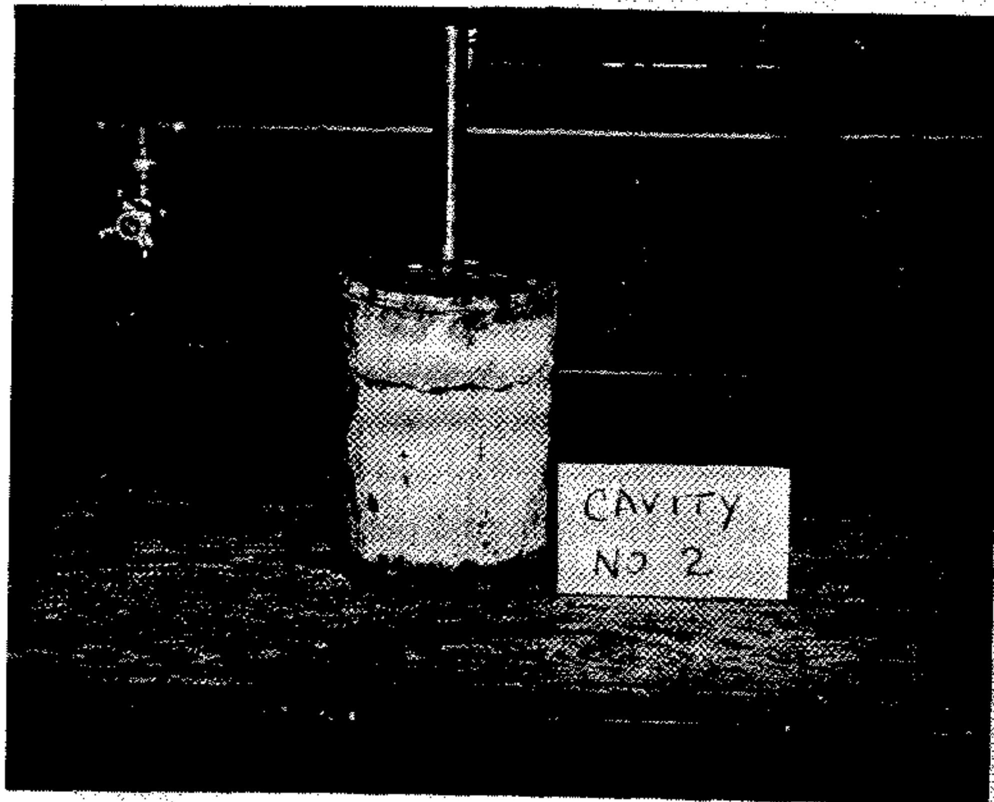


Figure 7. Core No. 2 After Removal from Test Cylinder.

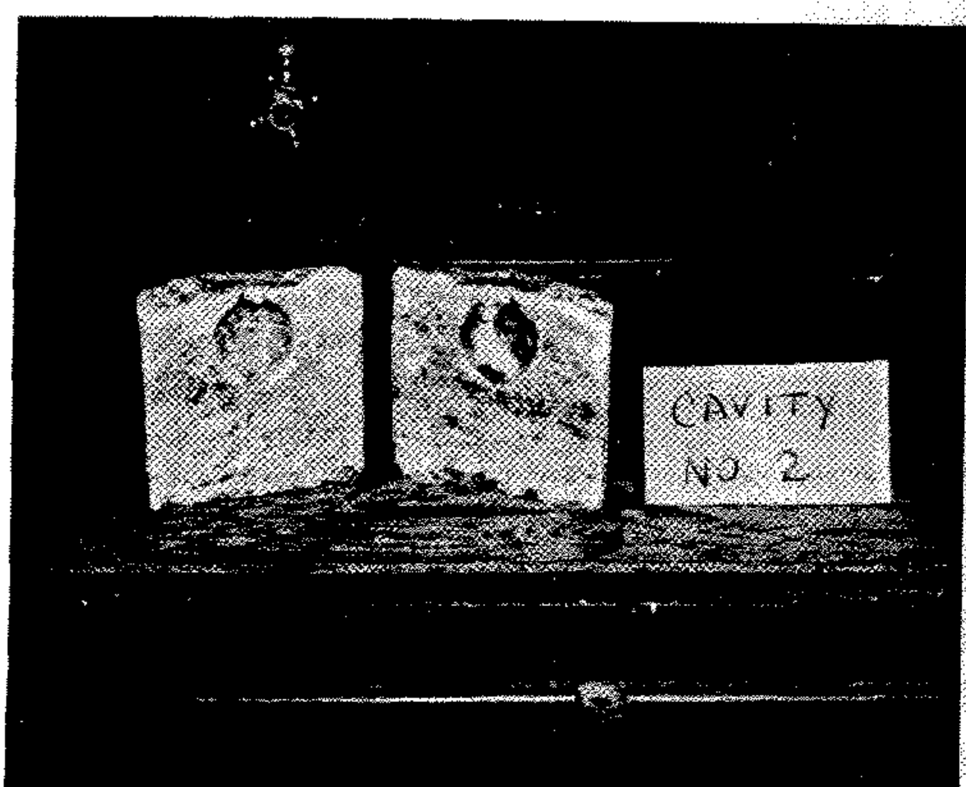


Figure 8. Core No. 2 Cut in Half.

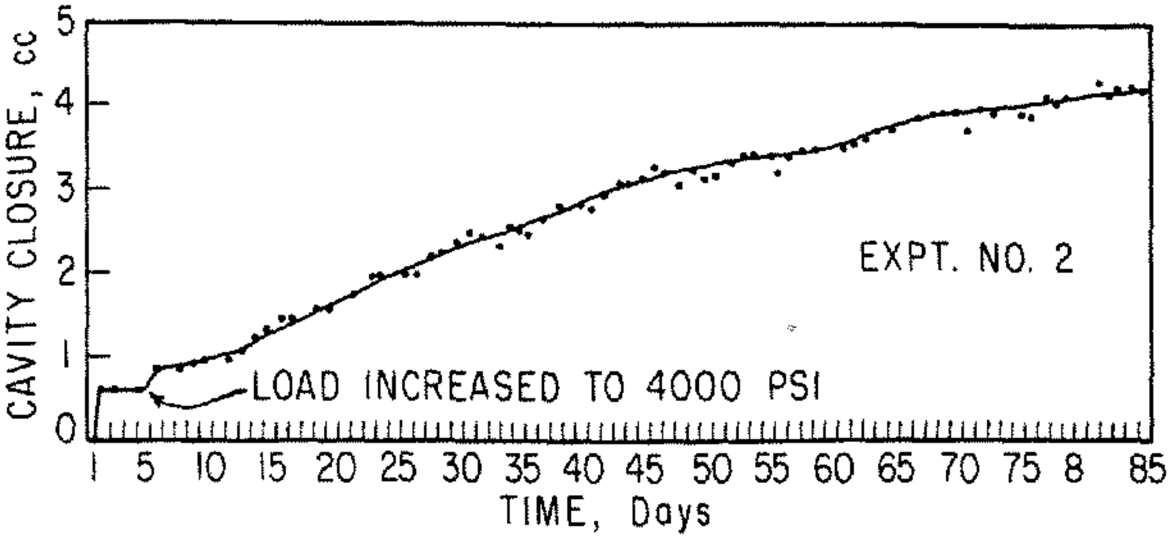


Figure 9. Cavity Volume Change.

3,000 psi. The core was to be held at 3,000 psi for a sufficient period of time to predict rea-
able structural stability. Refinements in measuring cavity volume and changes in volume were
orporated in this and all subsequent trials.

After placing the core in the test cylinder, the temperature was allowed to stabilize at ± 2°F. The scheduled rate of loading was in increments of 41 psi per hour during the day. ere was no loading during the night. After a period of six days the maximum stress of 3,000 psi s reached. The slow loading rate was to simulate field conditions of cavity leaching. However, ing the first day after the core was loaded to 287 psi, the load was accidently increased to 1,200 in one increment but was immediately reduced to 328 psi. The effects of changing loading in- ments are discussed elsewhere.

After continuing the test for a period of 22 days, the temperature sensitive relay controlling electric heaters became jammed. This caused the heaters to remain on. It was impossible to ermine the maximum temperature reached since the excessive heat caused the wires supplying electric current to the heaters to burn out. It was estimated the temperature exceeded 400°F l even may have risen to 500°F. Due to the abnormal temperature, approximately 95% closure s observed to have taken place during the time elapsed between readings -- a period of eight irs. Such rapid closure could have proceeded only under conditions of extremely high tempera- e, that is, above 400°F. Figure 10 shows Core No. 3 cut in half. Examination of the core nd specimen) showed plastic flow of the salt greatest near the cavity.

1. Observable deformation of salt crystals was extreme within the region bounded by the former walls of the cavity;
2. There was a fine-grained appearance in the vicinity of the original boundary of the cavity;
3. The number of fractures decreased away from the cavity; and
4. The limit of visible deformation was approximately one inch away from the former cavity center.

Further investigations with thin sections taken from different locations around the core sub- ntiated the above conclusions. Details of the study of the thin sections are discussed later.

During the period of 22 days (before collapse of the cavity) the cavity volume was reduced 4786 cc (original cavity volume was 17.851 cc). This represents a closure of 2.68%. It was ob- rved that very little deformation of the cavity occurred until a stress of 1,090 psi was reached. hough the test was terminated prematurely, the shape of the curve suggests the largest part of vity deformation had occurred prior to the equipment failure.

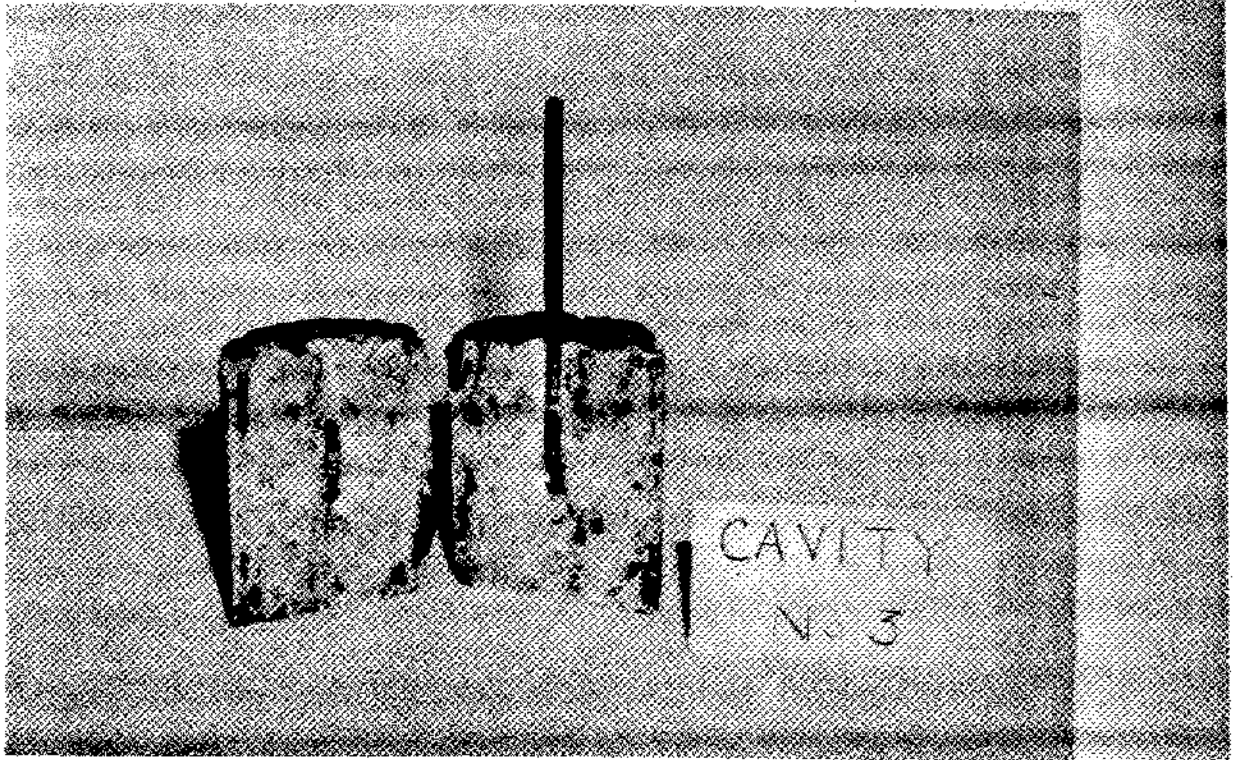


Figure 10. Core No. 3 Cut in Half.

Experiment No. 4

The purpose of this test was the same as outlined previously for Experiment No. 3 on Core No. 3, but rate of loading was increased so that the maximum load would be reached within a shorter length of time.

After placing the core in the test cylinder the temperature was allowed to stabilize. With the installation of a third thermocouple to record the temperature at the center of the cavity, it was possible to determine the temperature gradient through the core. The temperature at the center of the core was 126 ± 3°F, while the temperature at the side of the core was 128 ± 3°F. Thus, there was an average gradient of 2°F through the salt. Pressure was applied to the core in uniform increments of 102 psi per hour over a period of 29 hours until the maximum stress of 3,000 psi was reached. Constant pressure was maintained for the duration of the test.

After 88 days Core No. 4 was removed from the test cylinder. No difficulties were encountered during the testing of this core. Figure Nos. 9 and 10 show the core after removal from the test cylinder before and after being cut vertically in half. Figure 11 shows the decrease in cavity volume versus time. A smooth curve was drawn through all points plotted. The following function was completed by a trial-and-error solution to closely fit the last 54 days of the test period.

$$V = Ae^{-\gamma t} + B \qquad \text{(Eq. 1)}$$

V = cavity closure, cc $\times 10^{-2}$, at time, t

A = -29.0 (a constant)

γ = 0.0453 (a constant)

e = the base of the Napierian Logarithim

t = time, days

B = 50.20, cc $\times 10^{-2}$ (cavity closure at time = ∞)

Utilizing the preceding equation, the ultimate cavity closure would be 0.5020 cc for a spher-
il cavity whose initial volume was 19.020 cc, i.e., 2.64% cavity closure at structural equilib-
ım. Upon termination of this test, a total closure of 0.4967 cc was observed which represented
:avity closure of 2.61% of its initial volume. Therefore, after 88 days, 98.98% of the expected
.imate closure had taken place.

Figure 12 shows the vertical strain versus time for Core No. 4.

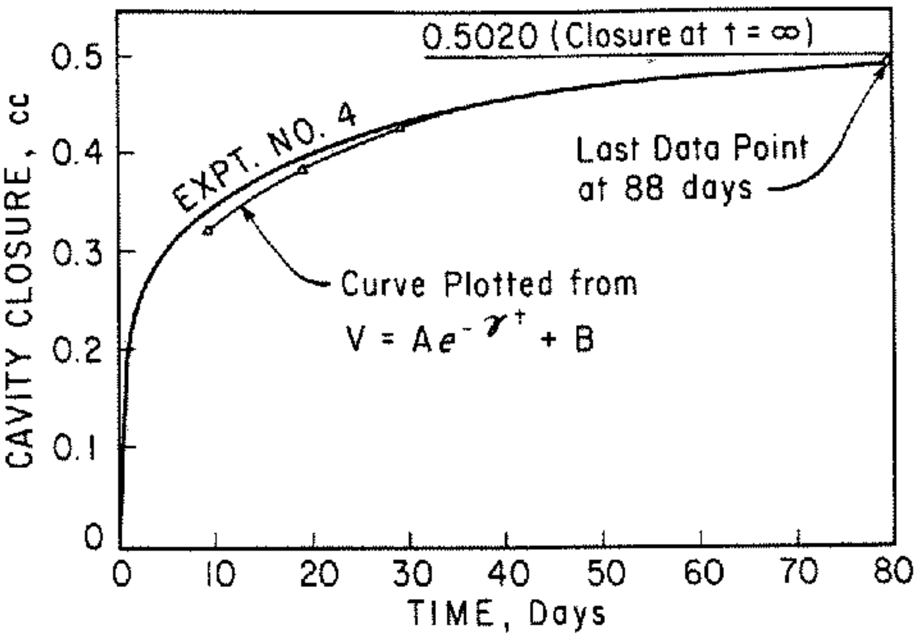


Figure 11. Cavity Volume Change.

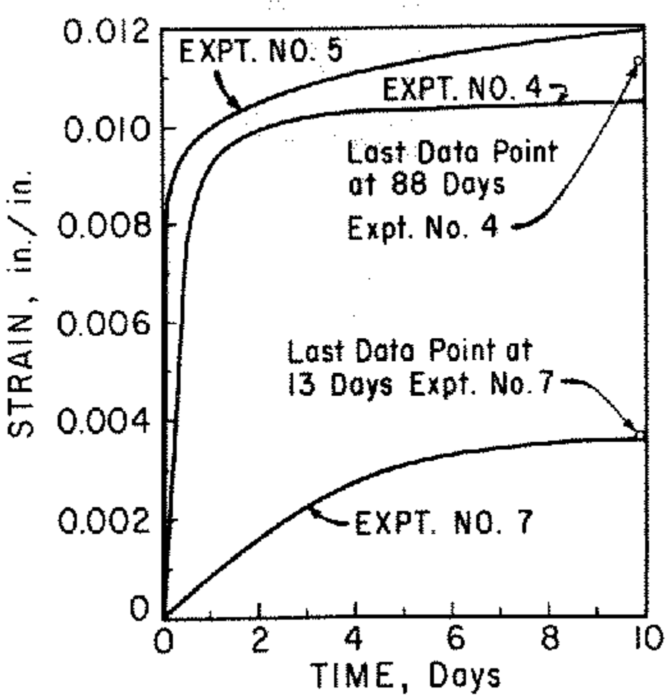


Figure 12. Vertical Deformation of Salt Core.

Experiment No. 5

The purposes of this test were to study the effects resulting from a very fast rate of application of the load and to compare the results after ten days with those obtained after testing Core Nos. 3 and 4.

The temperature was stabilized at 125 ± 2°F at the center of the core and 127 ± 2°F at the side of the core. Pressure was applied to the core uniformly but rapidly for a period of only five minutes until the maximum load of 3,000 psi was reached, after which it was held constant.

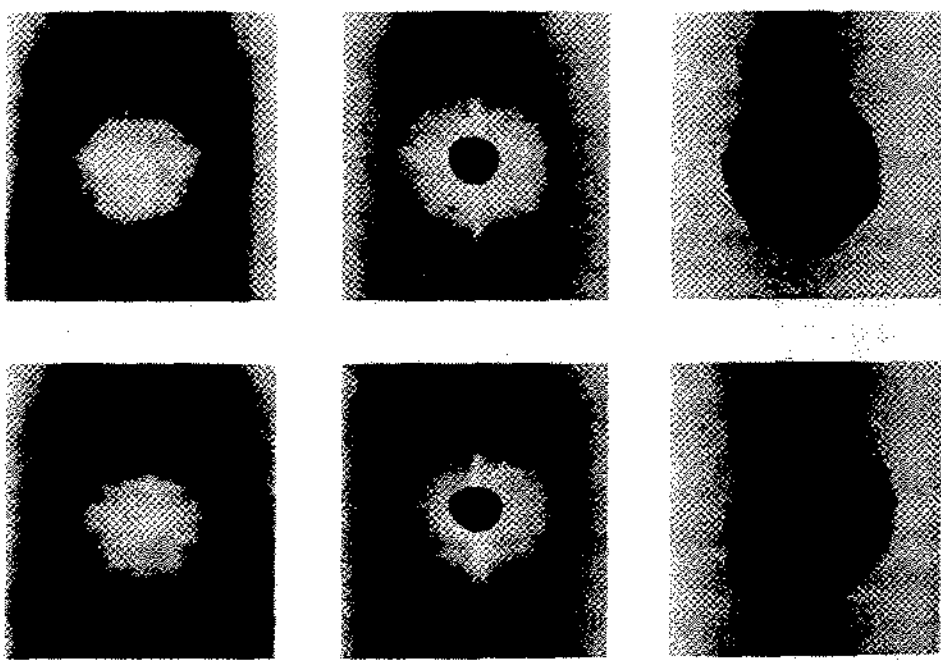
After ten days, Core No. 5 was removed from the test cylinder. During the ten-day period the cavity volume was reduced 0.4686 cc, representing a closure of 2.17%. The expected ultimate closure was 0.570 cc for this cavity. Therefore, after ten days 82% of the expected ultimate closure had taken place.

A series of X-ray photographs of Core No. 5 are shown in Fig. 13 to indicate the outline of the cavity (1) after it was completed with the cutting tool, (2) before being put into the test cylinder with the casing cemented in place, and (3) after completion of the test. The dark spot in the center of the cavity shown in the second set of photographs was caused by a drop of mercury that was not removed from the cavity. The dark outline of the cavity shown in the third set was the result of having the cavity full of mercury.

After measurement of these photographs, the only visual deformation observed was a slightly shortened vertical dimension of the cavity.

Experiment No. 6

The purpose of this test was to obtain specimens for thin section study exclusively. Since fractures and cracks developed after initial stress conditions were established might anneal due to the length of time the sample was maintained at an elevated temperature under constant load, it was decided to obtain specimens as quickly as possible after the initial stresses had been induced.



(1) (2) (3)

Figure 13. X-Ray Photographs of the Cavity in Core No. 5. The Two Views are at Right Angles to Each Other and Enlarged 1.29/1.

by loading. It was hoped that under such conditions fractures and cracks, not found in thin sections taken from Core No. 4, would be revealed.

After placing the core in the test cylinder the temperature was stabilized at 127 ± 2°F at the center of the core. Load was applied at a uniform rate for a five-minute period until the maximum load of 3,000 psi was reached. This load was held constant for an additional fifteen minutes. Then the core was removed from the test cylinder, and specimens immediately cut from the core with a diamond saw and shipped to laboratories in California for preparation of thin sections. The thin sections were received five days later and examined immediately. The results of this experiment are shown under the heading Thin Section Study.

Experiment No. 7

The purpose of this test was to determine the effects of slow rate of application of load.

After placing the core in the test cylinder the temperature was allowed to stabilize at 124 ± 2°F at the center of the core and 128 ± 2°F at the side of the core. Pressure was applied uniformly for a period of 4-1/4 days in increments of 177 psi every six hours until the maximum load of 3,000 psi was reached which was then held constant.

After 13 days, Core No. 7 was removed from the test cylinder. No difficulties were encountered during the testing of this core. During the 13-day period, the cavity volume was reduced 0.156 cc. With an initial volume of 19.75 cc this represents a closure of 0.79%. Both the percent of cavity closure and vertical deformation of Core No. 7 were less than that for Core Nos. 4 and 5 which were loaded at a faster rate.

Figure 14 shows the time rate of closure, $\frac{dv}{dt}$ divided by the initial cavity volume, v, versus time, t, for Core Nos. 2, 3, 4, 5, and 7. In all cases the rate of closure decreases rapidly during the first five or six days and then approaches zero almost asymptotically. However, the curve drawn for Core No. 2 approaches zero decidedly slower than does the curve for Core No. 4 showing that the cavity at 3,000 psi and 130°F was nearer structural stability after 88 days than the cavity at 4,000 psi and 130°F after 85 days.

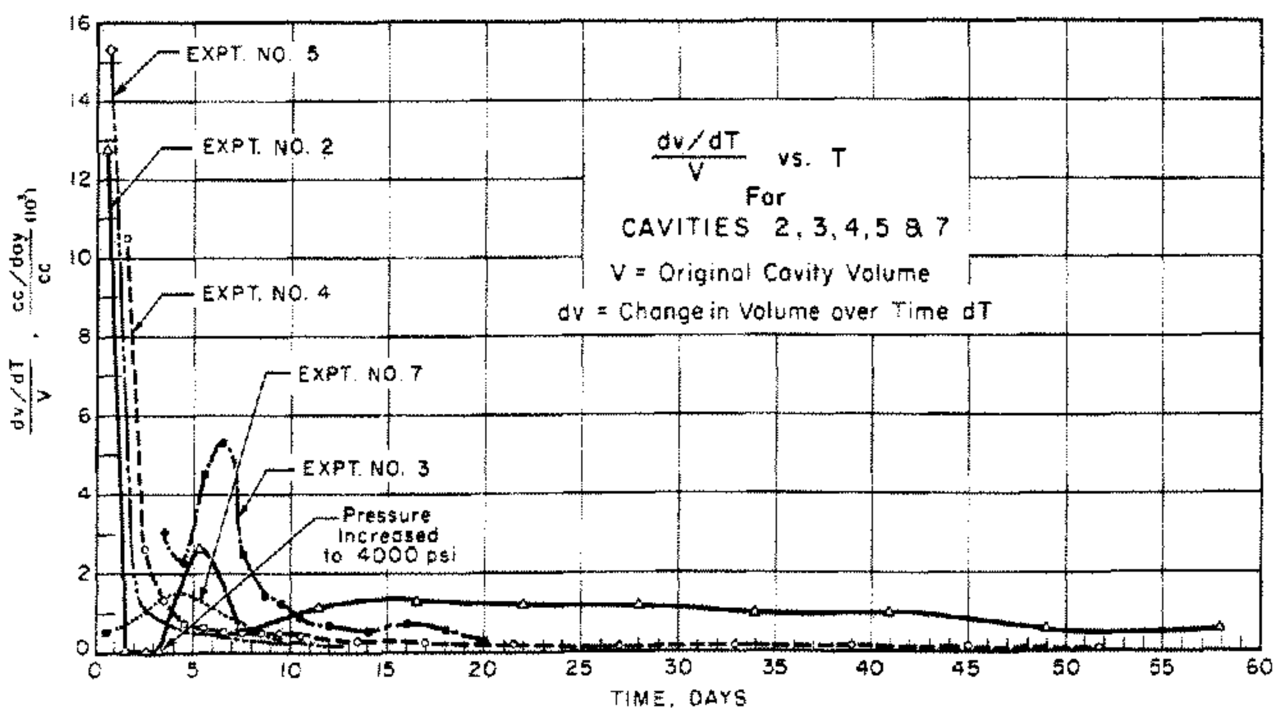


Figure 14. Rate of Cavity Closure.

Figure 15 shows the percentage of cavity closure versus time for Core Nos. 3, 4, 5, and 7. During the first few days it is apparent that the rate of loading influences the extent of early deformation. However, a critical analysis of the observed differences, when considered in the light of the total pressure (in psi) exerted on the core, indicates a much greater agreement in the volume change experienced. For example, total load after two days time for Core No. 3 was only 1,100 psi, and this loading was reached in 11 hours in Core No. 4, and in a matter of minutes in Core No. 5. The curve drawn for Core No. 3 exhibits the same general shape after this degree of loading. That the same condition did not occur in the case of Core No. 7 is not readily explained. Perhaps a greater binding of cement to the wall of the cylinder resulted causing somewhat more friction effect. The relative strain developed during loading under confining pressure conditions at approximately the same rate of loading is about one-half that obtained in tests carried out under no confining pressure (6). Consequently, it is realized that some variation in salt movement, occasioned by the strain imposed, takes place during the various stages of loading, and during the entire testing period. An average curve, such as that shown in Fig. 15 represents results which may be expected for a number of tests within the rates of loading applied. Furthermore, after a period of ten days (or slightly more) approximately the same percentage of volume change has occurred. The latter portion of the average curve was constructed assuming the condition of pressure and temperature to be the same in each case, and after the initial portion was established, could conform to the general form expressed by Equation 1. Therefore, the latter portion of the average curve has the functional form of Equation 1 and approaches the asymptotic value, B, of 2.96%, the ultimate percentage cavity closure.

Figure 12 shows the vertical strain versus time for Core Nos. 4, 5, and 7. The curves indicate that a faster rate of loading results in a greater initial strain.

Griggs (7) and Serata (8) reported experimental data that showed increased plastic deformation of rocks as the rate of deformation within the creep range is increased. However, a further increase in the magnitude of the strain rates will tend to decrease the plastic deformation of the rocks before fracture (9).

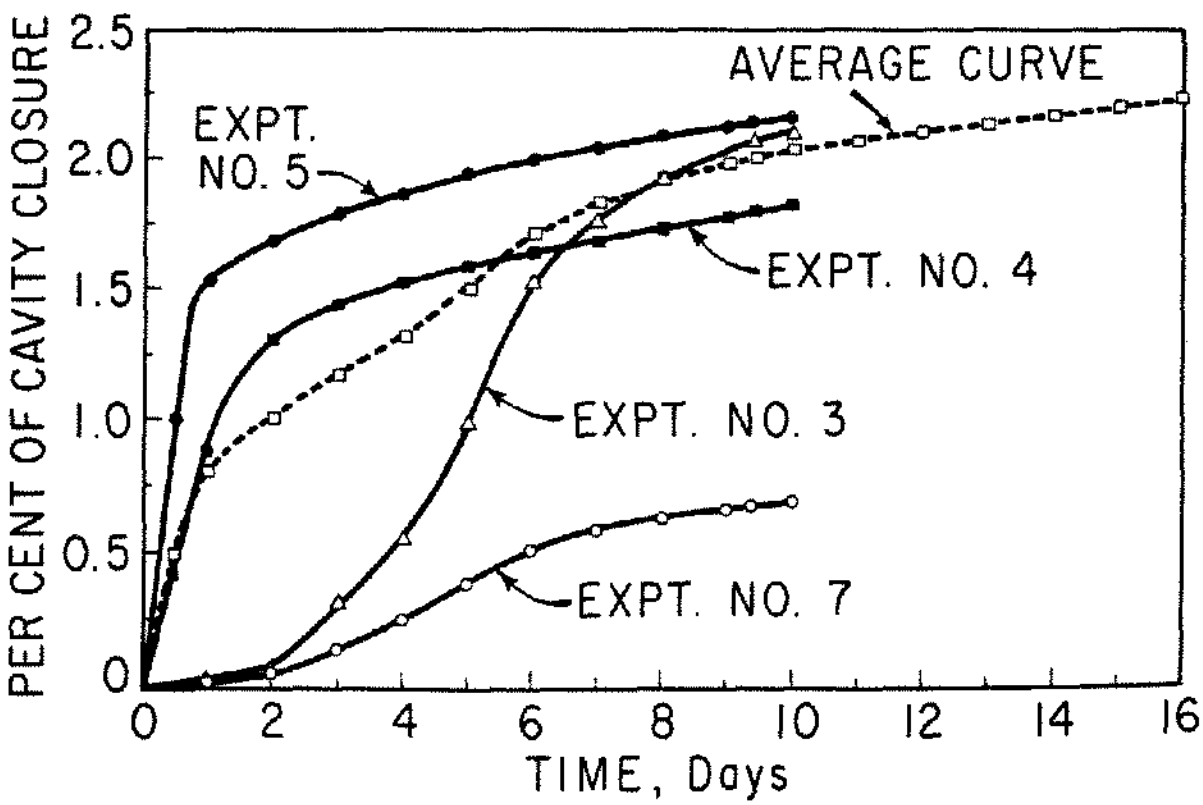


Figure 15. Cavity Closure.

General Discussion

Serata and Gloyna (1) derived an equation for the relation between the radius of the plastic front (in terms of the cavity radius) $\frac{\rho}{a}$, and the condition of the structural loading in terms of the pressure difference divided by the equivalent plastic limit, $\frac{P_o - P_i}{\sigma_o}$, for a given cavity temperature rise, T_c.

$$\frac{P_o - P_i}{\sigma_o} = 2 \ \ell n \frac{\rho}{a} + \frac{2}{3} - \frac{2}{3} \ \frac{\alpha E \ T_c}{\sigma_o (1 - \nu)} \ \frac{a}{\rho} \qquad \text{(Eq. 2)}$$

Where:

P_o = External pressure of cavity

P_i = Internal pressure of cavity

σ_o = Equivalent plastic limit of salt

ρ = Radius of plastic front

a = Radius of spherical cavity

T_c = Temperature rise in cavity

α = Coefficient of linear thermal expansion

E = Young's modulus

ν = Poisson's ratio

For the conditions of Core No. 4, since no temperature increase was present in the cavity, (i.e., $T_c = 0$), the radius of the plastic front is computed to be 1.27 inches. This value is well within boundary conditions fixed by the dimensions of the original cavity and the salt core, and hence results of closure measurements are held to be valid.

Reynolds and Gloyna (10) also derived an equation for linear creep in the 700-foot deep Grand Saline, Texas, salt mine.

$$\frac{d\epsilon}{dt} = \text{creep rate} = 0.03e^{-0.635t} \qquad \text{(Eq. 3)}$$

By taking the first derivative of Equation 1, the volumetric creep rate of the cavity in Core No. 4 can be obtained, i.e.

$$\frac{dV}{dt} = -\gamma A e^{-\gamma t}$$

$$\frac{dV}{dt} = - (0.0453)(-29)e^{-0.0453t}$$

$$\frac{dV}{dt} = 1.313e^{-0.0453t} \qquad \text{(Eq. 4)}$$

Equations 3 and 4 have the same functional form. The constants in the two equations are different because a linear creep rate is expressed in Equation 3 and a volumetric creep rate is expressed in Equation 4. Also, the conditions of pressure and temperature are different in the two cases.

A comparison of the experimental results and predicted ultimate closure is given in Table I. The experimental values determined are subject to two sources of error, both of which are considered to be small. First, the friction force created on the surface of the specimen exposed to the metal surface of the test cylinder and piston, and second, excessive lateral strain of the salt specimen allowed by the thin paraffin-kerosene coating on the inside of the test cylinder. These two factors represent the greatest difference between actual underground conditions and conditions created in the test cylinder.

The deviation between the results of Experiment Nos. 3 and 7 which were conducted under nearly identical conditions is attributed to the above sources of error. Before placing Core No. 3

TABLE I

Core No.	Cavity Diameter Inches	Cavity Volume		Volume Change		Ultimate Closure Predicted from Avg. Curve	Temp. °F	Final Pres. psi.	Rate of Loading	Duration of Tests, days
		Initial	Final	ml	% of Initial					
1	1.86	55.0	--	--	--	--	130	--	--	Failed to obtained seal. Abandoned
2	1.86	55.0	54.4	0.6	1.1	--	132	3,000	600 psi/ 5 min. Then constant	4
		55.0	50.9	4.1	7.45 after 88 days	--	132	4,000	500 psi/ 5 min. Then constant	85
3	1.28	17.851	--	--	2.48 after 22 days	95% total closure	130	3,000	40 psi/hr. Then constant	22 (Test terminated because of temp. control failure allowing max. temp. to exceed 400°F)
4	1.30	19.020	18.573	.497	2.61 after 88 days	2.96%	130	3,000	102 psi/hr. for 29 hrs. Then constant	88
5	1.36	21.635	21.167	.468	2.17 after 10 days	2.96%	130	3,000	3,000 psi/ 5 min. Then constant	10
6	1.35*	--	--	--	--	--	130	3,000	3,000 psi/ 5 min. Held for 15 min. only	20 min.
7	1.32	19.750	19.594	.156	0.79	2.96%	130	3,000	175 psi/6 hrs. Then constant	13

* Initial volume approximately same as for cavity No. 5. No measurements made since test designed to yield information from thin section study **only.**

and all other cores except Core No. 7) in the test cylinder, the inside of the cylinder and all metal parts in contact with the specimen were coated with a hot solution of paraffin and kerosene, whereas before placing Core No. 7 in the cylinder a room temperature solution of paraffin and kerosene was used. A somewhat thicker film of paraffin may have resulted from the use of the hot kerosene-paraffin solution. This heavier film would reduce friction and allow greater lateral strain. Both effects would cause greater cavity deformation.

THIN SECTION STUDY

The thin section study was conducted to determine any relation between the movement of the salt and the resulting patterns of microfractures and cracks, and the nature of movement of the salt.

Thin section samples were taken from three different cores. Eight sections were taken from Core No. 3, four from core No. 4, and four from Core No. 6. Figures 16 and 17 show the locations of segments from which thin sections were made.

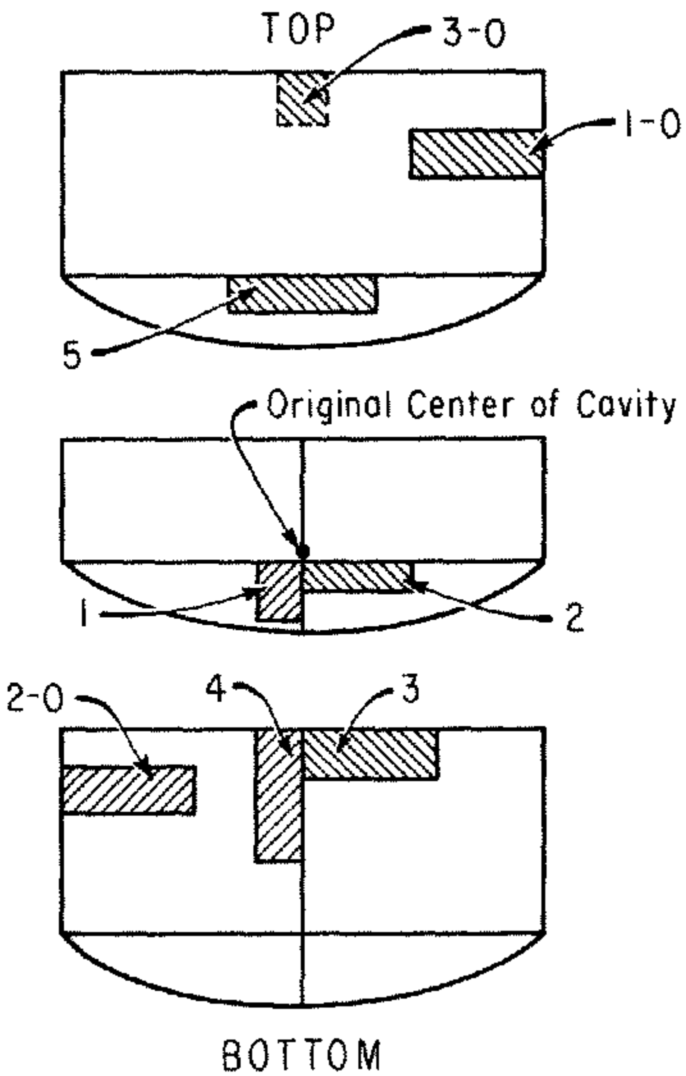


Figure 16. Thin Sections Locations Core No. 3.

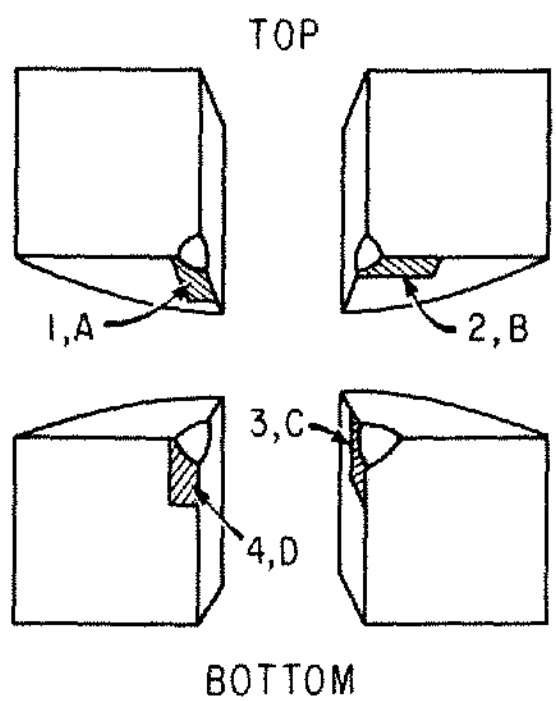


Figure 17. Thin Sections Locations Core Nos. 4, 8, 6 (Core No. 4 -- Sections 1, 2, 3, 4 and Core No. 6 Sections A, B, C, D).

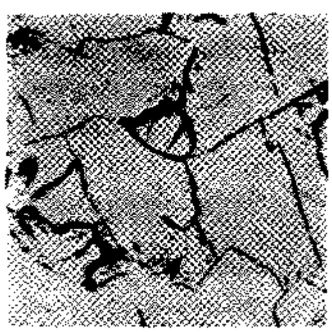
Core No. 3 was subjected to 3,000 psi and 130°F for 22 days before the temperature was accidentally increased to over 400°F which caused a rapid rate of deformation and approximately 95% cavity closure. Core No. 4 was subjected to a constant pressure and temperature of 3,000 psi and 128°F for a period of 88 days, which resulted in a cavity closure of 2.61%. Core No. 6 was subjected to a rapid rate of pressure increase and a constant pressure of 3,000 psi at 128°F for a period of only 20 minutes.

The thin sections from Core No. 3 proved to be the most interesting. Two distinct zones of different type fractures are evident. Within a radius of approximately 3/4 inch from the center of the cavity the fractures are irregular curves and possess no symmetry. See Fig. 18. These fractures are indicative of the increased flow rate at the cavity boundary as the salt moved radially into the cavity. Farther from the cavity center where the flow rate was less, the fracture pattern becomes more systematic as cleavage cracks and en echelon fractures become dominant. See Fig. 19. Groups of fractures in unusual herringbone patterns are found throughout the outer zone, but these are more abundant toward the original boundary of the cavity. These unusual patterns appear to develop from intersecting groups of en echelon fractures. See Fig. 20.

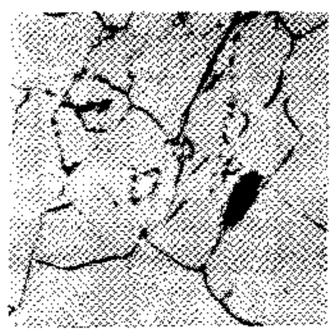
The fracture patterns seen in the thin sections from Core No. 4 are generally of one type. Fine cleavage cracks are dominant with some en echelon fractures. There is apparent no zone of random or erratic fracturing. Typical fracture patterns are shown in Fig. 21.

The fracture patterns seen in the thin sections from Core No. 6 are primarily coarse (wider) cleavage cracks with no apparent zone of random or erratic fracturing. Typical patterns are shown in Fig. 22. The coarse nature of these cleavage cracks, relative to those found in Core No. 4, imparts substance to the assumption that an extended testing period permits annealing of fractures and cracks initially developed.

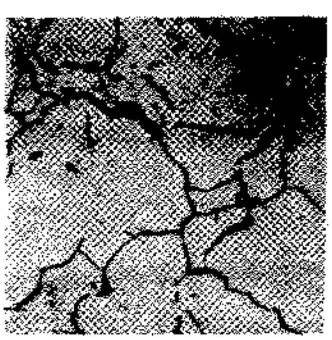
The cleavage cracks found are evidence of brittle failure rather than plastic flow. Since some cracks and fractures could have been developed during preparation of the thin sections, no conclusive evidence of the nature of the salt movement is possible from this examination.



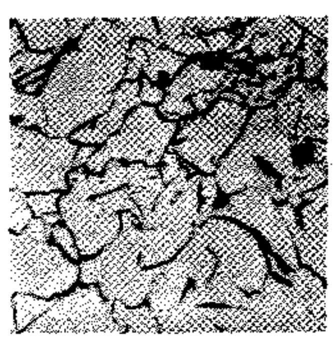
1. FROM SLIDE 4, 25X



2. FROM SLIDE 5, 25X



3. FROM SLIDE 2, 25X



4. FROM SLIDE 1, 25X

Figure 18. Thin Sections from Core No. 3.

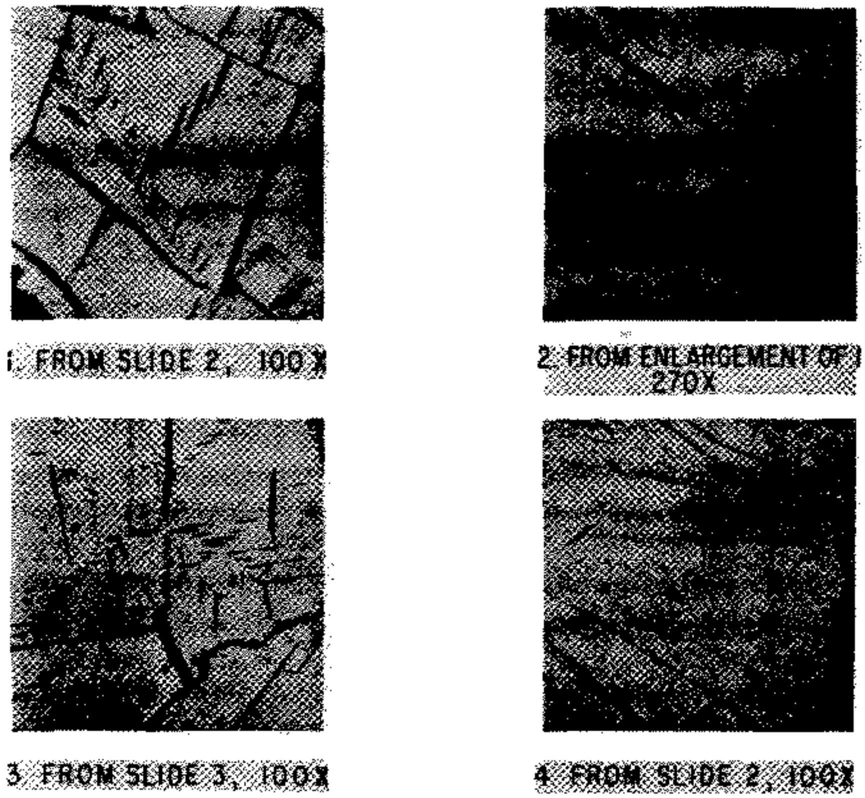


Figure 19. Thin Sections from Core No. 3.

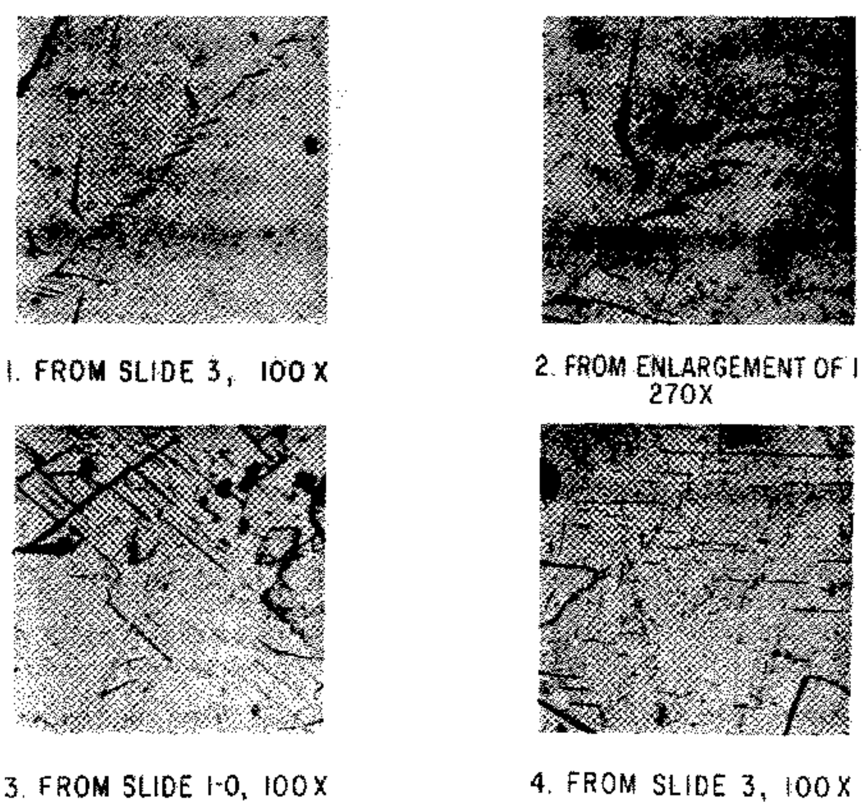


Figure 20. Thin Sections from Core No. 3.

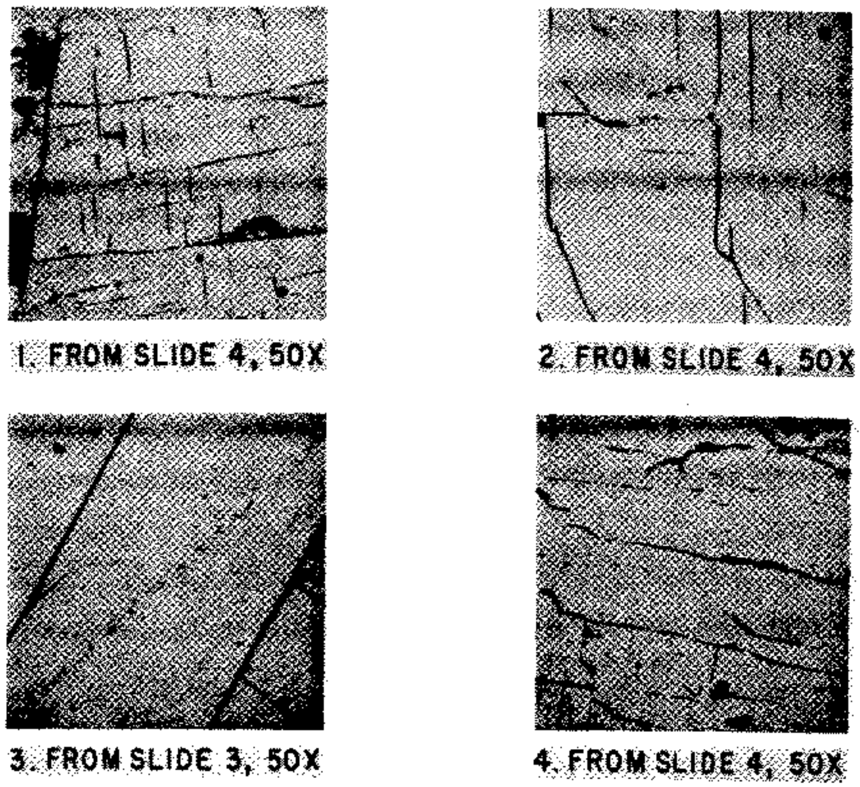


Figure 21. Thin Sections from Core No. 4.

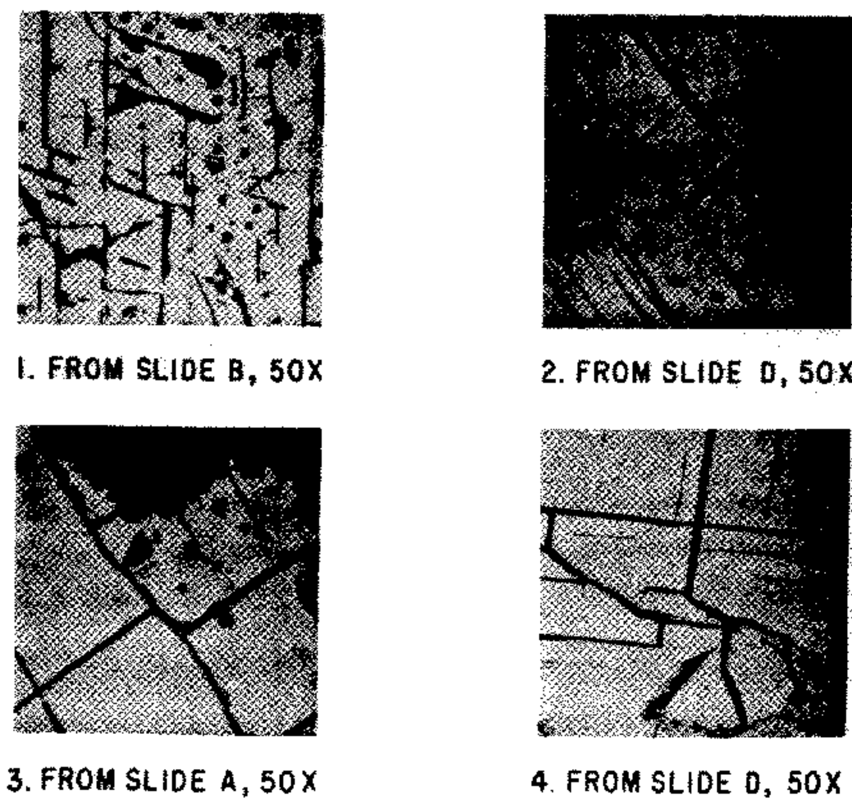


Figure 22. Thin Sections from Core No. 6.

/ever, the direction of movement of the salt can be demonstrated clearly with the en echelon :erns which give the relative slip directions of the segments of salt bounding the fracture sys-

ACKNOWLEDGMENT

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REFERENCES

S. Serata and E. F. Gloyna: "Development of Design Principle for Disposal of Reactor Fuel Waste Into Underground Salt Cavities," The University of Texas, January 1, 1959.

D. R. Remson: "Model Studies of Techniques for Dissolving Spherical Cavities in Massive Salt," M.S. Thesis, The University of Texas, January 1963.

R.O. Caudle and G.B. Clark: "Stress Around Mine Openings in Some Simple Geologic Structures," Engr. Experiment Station Bulletin No. 430, University of Ill., vol. 52, no. 69, May 1955.

Kermit E. Brown: "Pressure-Temperature Effect on Salt Cavities and Survey of Liquefied Petroleum Gas Storage," Jour. Pet. Tech., vol. 216, pp. 341-345, 1959.

United States Dept. of the Interior Bureau of Reclamation: "Triaxial Compression Tests of Salt Rock Cores for the United States Atomic Energy Commission -- Project Dribble," Division of Engineering Laboratories Report No. C-1043, October 29, 1962. Division of Engineering Laboratories, Office of Asst. Commissioner and Chief Engineer, Denver, Colorado.

United States Army Engr. Waterways Experiment Station: "Project Dribble Petrographic Examination and Physical Tests of Cores, Tatum Salt Dome, Mississippi," Corps of Engineers Technical Report No. 6-614, January 1963.

D.T. Griggs: "Deformation of Rocks Under High Confining Pressures," Jour. Geol., vol. 44, no. 5, pp. 541-577, July-August 1936.

S. Serata: "Transition from Elastic to Plastic States of Rocks Under Triaxial Compression," Bull. of the Mineral Industries Experiment Station, Fourth Symposium on Rock Mechanics, Penn. State Univ., pp. 75-79, March 30, 1961.

S. Serdengecti and G.D. Boozer: "The Effects of Strain Rate and Temperature on the Behavior of Rocks Subjected to Triaxial Compression," Bull. of the Mineral Industries Experiment Station, Fourth Symposium on Rock Mechanics, pp. 81-32, Penn. State Univ., March 30, 1961.

T.D. Reynolds and E.F. Gloyna: "Creep Measurements in Salt Mines," Bull. of the Mineral Industries Experiment Station, Fourth Symposium on Rock Mechanics, pp. 12-14, Penn. State Univ., March 30, 1961.