Model Studies in Solution Mining

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ABSTRACT

Experiments simulating the formation of field salt solution cavities were conducted in the laboratory. The purpose of these tests was to determine the influence of the injection pipe position and the cavity height on the vertical salinity gradient in the cavity. The results show a marked effect of the pipe position on the initial vertical salinity gradient and with it on the cavity shape. It was also found that long narrow cavities could result in a density inversion within the bulk fluid and as a result lead to initially "bottle shaped" cavities.

INTRODUCTION

The potential usefulness of underground solution caverns created by the solution mining industry has long been recognized (Jacoby 1970).

Their usefulness depends to a high degree on their stability. If not structurally sound the eventual closing of the cavern will lead to undesirable subsidence phenomena and may become a major burden on an organization's budget. A stable cavern, on the other hand, may turn into an asset. The geometry of the cavern is the most important factor regarding the stability of the structure. Techniques to develop predetermined cavity shapes are available (Remson, Dommers, Jessen 1966). Frequently these techniques are unacceptable for economical reasons. A number of measures, however, may be applied economically to influence the salinity distribution in the cavity and thus afford some control over the cavern shape.

The purpose of this paper is to present the results of a series of model tests in which the influence of some of these factors on the salinity gradient and the shape of the cavern was studied. The experiments fall into two groups:

1. The influence of the pipe position on the vertical salinity gradient in a cavity.

2. The influence of the cavity height on the vertical salinity gradient in a cavity.

INFLUENCE OF PIPE POSITION ON VERTICAL SALINITY GRADIENT IN A CAVITY

A model cavity in a 61 cm X 76 cm X 76 cm salt block was leached with the objective of studying the mechanism of salt solution as a function of the position of the injection pipe.

Preparation of the Model

After suitably sealing the outside of the block with an epoxy cement, a Lucite plate (51 cm X 56 cm X 1.27 cm) was glued to one of its sides. This plate provided a means for visual inspection of the cavity development as well as access to the cavity for sampling purposes. To this end, a 5.08 cm X 5.08 cm grid was drawn on the Lucite plate and at each corner a 0.635 cm diameter hole was drilled. These holes were subsequently sealed with rubber. Thus brine samples could be withdrawn from inside the cavity at any desired time by inserting hypodermic needles through the rubber seals. No leakage occurred during the insertion or withdrawal of the needles. For the initiation of the washing process, a 0.635 cm diameter, 47 cm deep hole was drilled vertically into the block at a location 2.54 cm away from the Lucite plate. The hole had a suitable enlargement at the top to accommodate a flow header.

Procedure

The cavity was washed using the reverse circulation method. The brine was discharged into graduated cylinders which provided a means of determining the flow rate. Hydrometer readings to three significant figures were used to determine the specific gravity of the effluent. The amount of salt removed was calculated from the measured volume of brine and its unit salt content. By adding the initial cavity volume to the amount of salt removed, a calculated value for the cavity volume was obtained. In addition, the cavity size and shape were measured by introducing saturated salt water into the emptied cavern. The control of injection, production and blanket fluid volume was accomplished through three concentric plexiglas tubes equipped with a suitably designed head. Brine samples of 1 cc to 2 cc volume were taken from inside the cavity with the help of syringes. An Abbey refractometer was used to determine the concentration of the samples. From these data the vertical and horizontal salinity profiles reported below were constructed.

The washing was carried out in five steps. Using the mobile pipe technique (cf. Remson, Dommers, Jessen 1966) the injection pipe was moved after each stage while the position of the production pipe remained fixed at 2.54 cm above the bottom of the borehole. For roof protection against leaching blanket fluid (kerosene) was used during the first four stages. The fifth stage was run without blanket fluid. The various stages 1–5 represent respectively near bottom injection, midpoint injection, quarterpoint injection, top injection with and without blanket fluid. As is common in such relatively large laboratory samples the block had several fractures in it which probably were introduced while mining it. They were discovered during the third washing stage because the epoxy cement had penetrated them leaving an insoluble trace. Their presence apparently did not appreciably influence the washing process during the first three stages. Table I represents a summary of the parameters that were used to control the washing process. The injection rate in each stage was adjusted such that saturated brine was produced.

Results

The results are presented in Figures 1–7 and in Table II. The figures represent graphs of the vertical and horizontal salinity gradient in the cavity for each washing stage. For a better understanding of the individual curves in each figure reference is made to Figure 7. It shows the sampling grid (Y_i, X_j, i, j = 1,10) on the Lucite sampling plate with the various stages of the cavity development drawn on it. The curves for the vertical salinity profiles were constructed from samples along columns X_j and those for the horizontal profiles from samples along rows Y_i.

The specific gravity along each horizontal plane up to a depth of 15.2 cm into the cavity (Fig. 1) remains relatively constant. This was found to be true for the horizontal profiles of the other washing stages as well. For this reason they are omitted here. More detailed data including complete production data are given elsewhere (Progress Report, December 1, 1970). The data shown for stage 1 in Figure 2 indicates the concentration variation in the vertical direction. Such a variation may be expected for the early stages of washing. The corresponding cavity

TABLE I

Experimental input data of cavity washing, stages 1 to 5

Stages	Washing Time (hrs.)	Injection Pipe Position (cm)*	Average Injection Rate (cc/min)	Volume of Water Circulated (cc)
First	122	3.8	5.4	39,506
Second	36	22.8	12	25,852
Third	51	11.4	13.8	41,300
Fourth	22	35.1	22.3	29,460
Fifth	8	35.1	23.6	11,370

*Distance from bottom of cavity.

TABLE II

Data showing calculated and measured volume of cavity intermediate injection

Stages	Initial Volume of Cavity (cc)	Volume of Salt Removed by Solution (cc)	Volume of Salt in Brine in Cavity (cc)	Volume of Insoluble Material (cc)	Total Volume Calculated (cc)	Total Volume Measured (cc)	Error %
First	400	5,558	903	139	6,600	6,750	2.2
Second	6,600	3,925	546	89	11,160	11,100	0.5
Third	(a)11,160	3,010	438	86	14,694	14,680	0.01
	(b)14,694	4,166	660	57	19.577	18,860	3.7
Fourth	19,577	4,159	1,042	116	24,894	—	—
Fifth	24,894	1,603	1,690	81	28,268	28,000	1.0

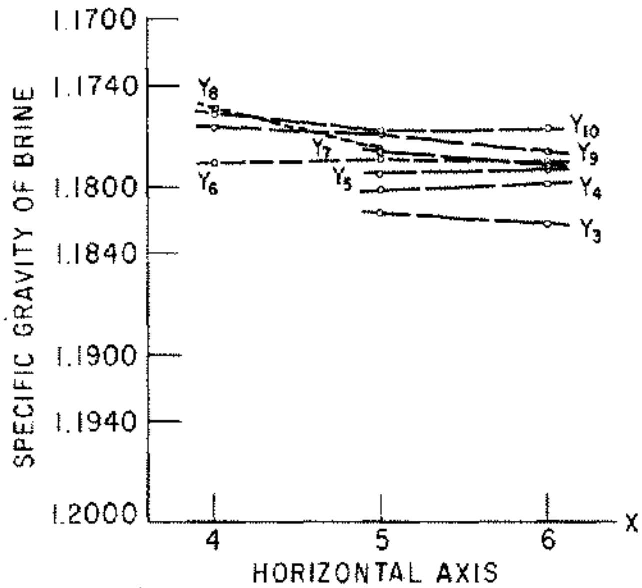

Figure 1. Horizontal brine concentration in cavity stage 1, bottom injection.

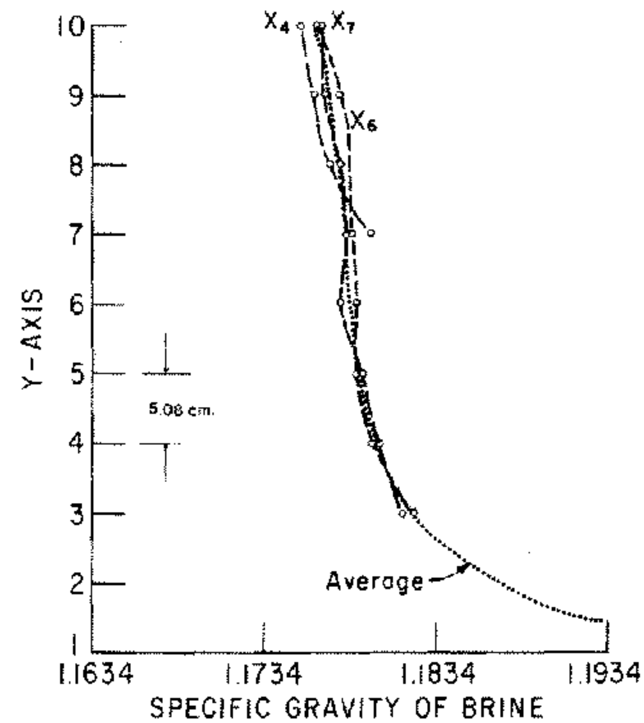

Figure 2. Vertical salt salinity profile in cavity stage 1, bottom injection.

shape is shown in Figure 7 curve 1. It is very nearly cylindrical except for the extreme top and bottom part. The large intrusion indicated on the right side of the cavity is due to an insoluble adhesive sheet resulting from sealing the fractures in the salt block. As mentioned earlier there was little effect shown on the normal cavity progress (left side) through stage 3 of the washing. This fact emphasizes the independence of the solution process on impurities as long as the flow pattern in the bulk fluid is not seriously impaired.

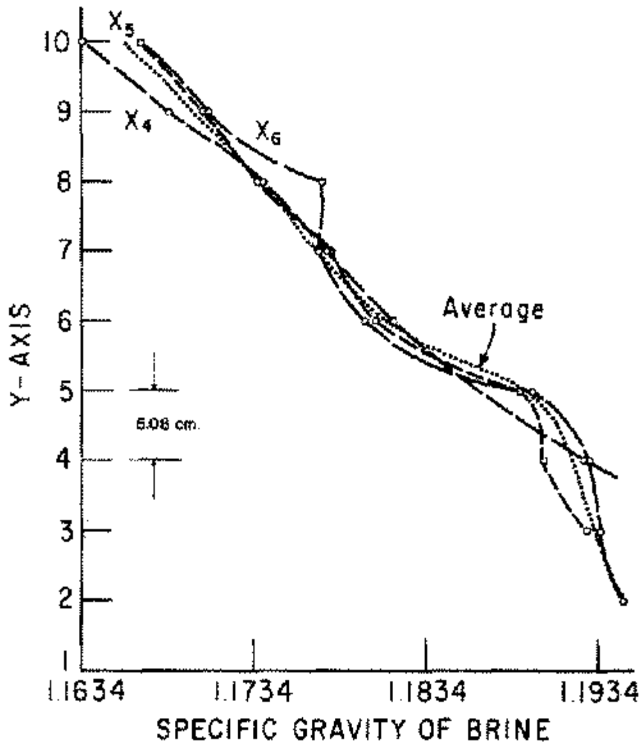

Figure 3. Vertical salt salinity profile in cavity stage 2, midpoint injection.

The effect of retracting the injection pipe to a mid-point position is illustrated in Figure 3. The specific gravity of the bulk fluid decreases rapidly above the injection point. It appears that mixing between fresh water and the bulk fluid is not as efficient as in stage 1. The associated cavity shape is illustrated in Figure 7 curve 2. As might be expected from the salinity profile a widening in the upper half of the cavity is clearly indicated.

The graph in Figure 4 represents the vertical salinity distribution during the third stage of washing (1/4 point injection). Above the injection point it resembles the shape of Figure 2 indicating that mixing in the lower portion of the cavity is quite effective. The corresponding cavity shape is given in Figure 3A and Figure 3B. The washing process had to be interrupted during this third stage because of leaks, developing in the salt block. After repair the experiment was resumed and the cavity enlarged to the shape indicated by 3B Figure 7.

In spite of the beginning difficulties and their effect on the cavity shape the experimental results obtained up to the first phase of stage 3 confirmed the solution mechanism postulated for cavity development using intermediate injection (Remson, Dommers, Jessen, 1966).

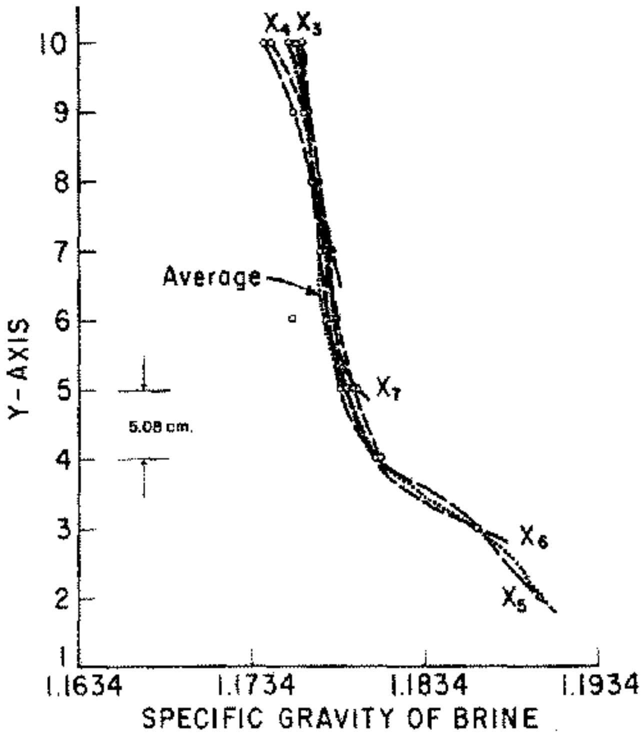

Figure 4. Vertical salt salinity profile in cavity stage 3, 1/4 from bottom injection.

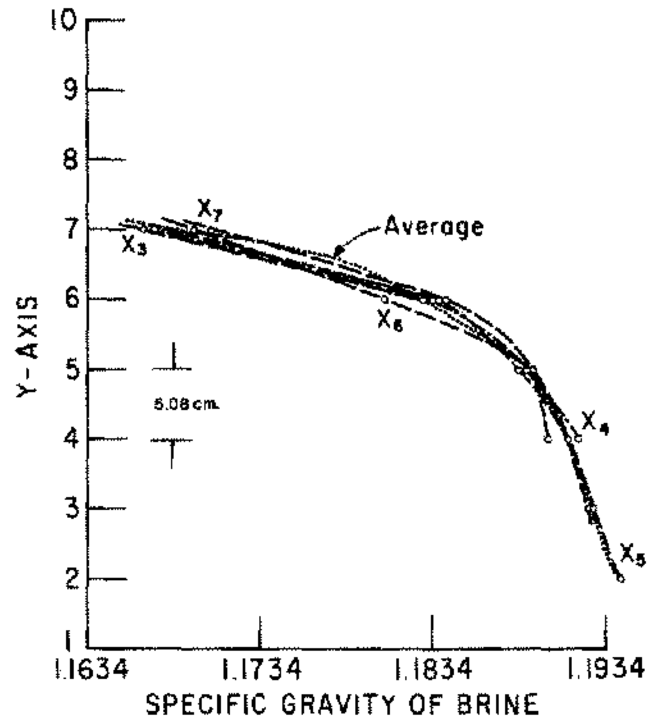

Figure 5. Vertical salt salinity profile in cavity stage 4, top injection.

Based on the vertical salinity gradients (Figs. 2, 3, 4,) and the rate of salt removal data reported in the literature (Durie and Jessen 1964) the expected cavity shape was computed for each stage and compared to the measured outline. As is illustrated in Figure 7 excellent agreement was obtained. The remaining two stages were run with top injection. Figure 5 gives the salinity profile for the case where blanket fluid was used to protect the roof from dissolution.

The shape of the curve represents a distinct departure from the previously shown ones. Due to top injection a relatively thin layer of fresh water formed at the top of the cavity which indicates that much less mixing takes place before the water reaches the salt face. In this case nearly all the regression in the cavity will take place in the top portion and lead to a "morning glory" shaped cavern.

Figure 6 represents the case where blanket fluid was absent. One of the more interesting points about this last washing stage is the relatively rapid increase in salinity which occurs from the solution of the roof. In Table II the data for the measured and calculated cavity volume in each stage is compared. In most cases the agreement is very good.

INFLUENCE OF THE CAVITY HEIGHT ON THE VERTICAL SALINITY GRADIENT IN A CAVITY

In previous experiments salt blocks of rather limited height (approximately 50 cm or less) were used. The initial

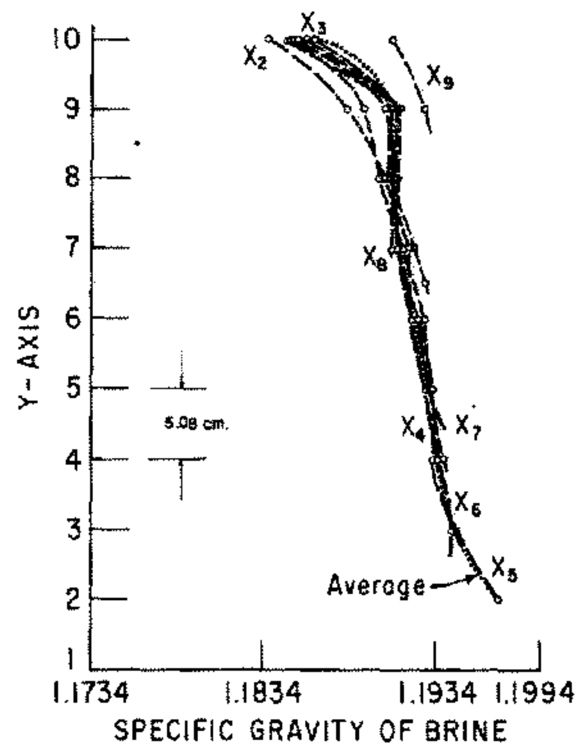

Figure 6. Vertical salt salinity profile in cavity stage 5, top injection, no blanket fluid.

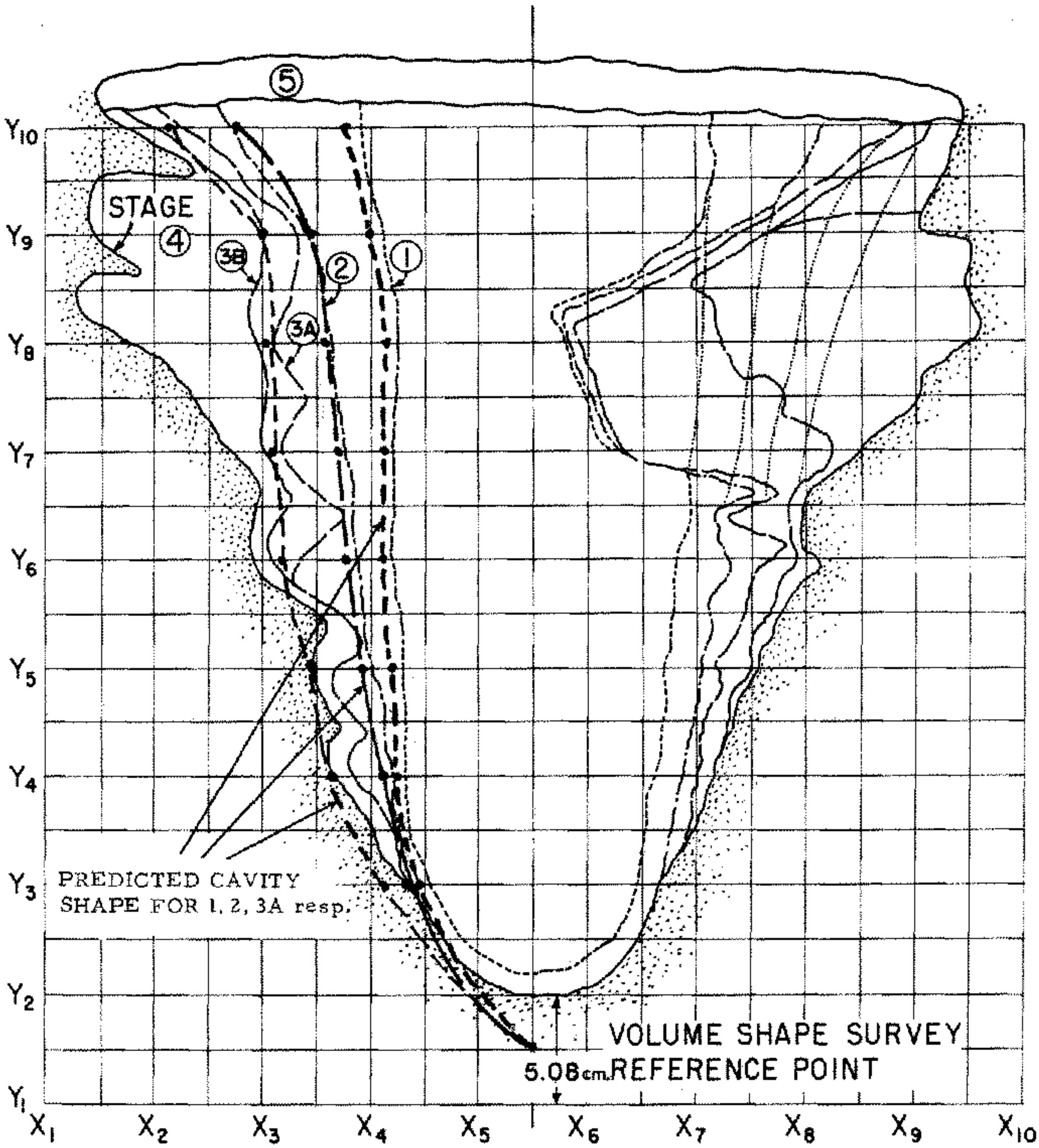

Figure 7. Cavity progression—intermediate injection point operation.

diameter to height ratios (H/D) in most cases varied between $10 \leq H/D \leq 20$. It is thought that besides H/D the height (H) of the cavity has a significant influence on the shape development at a given rate of injection.

Preparation of the salt block

The salt block was prepared in a way similar to that described above. A 1.27 cm diameter vertical hole was drilled to a depth of 117 cm which provided H/D = 92. This ratio is a little closer to those commonly occurring in the field. Other significant differences to previous tests were the provision of a sump at the bottom of the borehole and the location of the borehole drilled directly down the face of the salt block. The sump was introduced to hold the 5% insolubles. This permitted a mining process uninterrupted by cleaning operations. The location of the initial borehole provided a means of taking brine samples from inside the cavity from the very beginning of the washing process.

Procedure

The leaching process was carried out in 2 stages using the reverse circulation method after the sumps were constructed.

The rate of production was kept fairly constant and the effluent concentration was determined at regular intervals to provide the data for the calculation of the salt removed. Brine samples from inside the cavern were taken at four different times during stage 2 using the technique described above. From these data the salinity profiles presented below were constructed. The above data again are summarized in table form (Table III). At the end of each stage the shape of the cavity was determined.

Separation of the Lucite plate from the salt block had forced a termination of stage 1. Since the cavity was exposed the first shape survey was done by measuring the diameter of the cavity at various points along the vertical, the second shape survey was accomplished by adding incremental volumes of saturated brine to the emptied cavity as well as contouring it on the Lucite plate.

Results

The measured and calculated cavity volume based on the effluent concentration is compared in Table IV. The agreement is very good.

Salinity profiles determined for various time intervals of the stage 2 washing are presented in Figure 8. Of particular interest is curve 1 since it represents the case where heavier (higher saturation) fluid rests on top of lighter (lower saturation) fluid. The implications of such a salinity

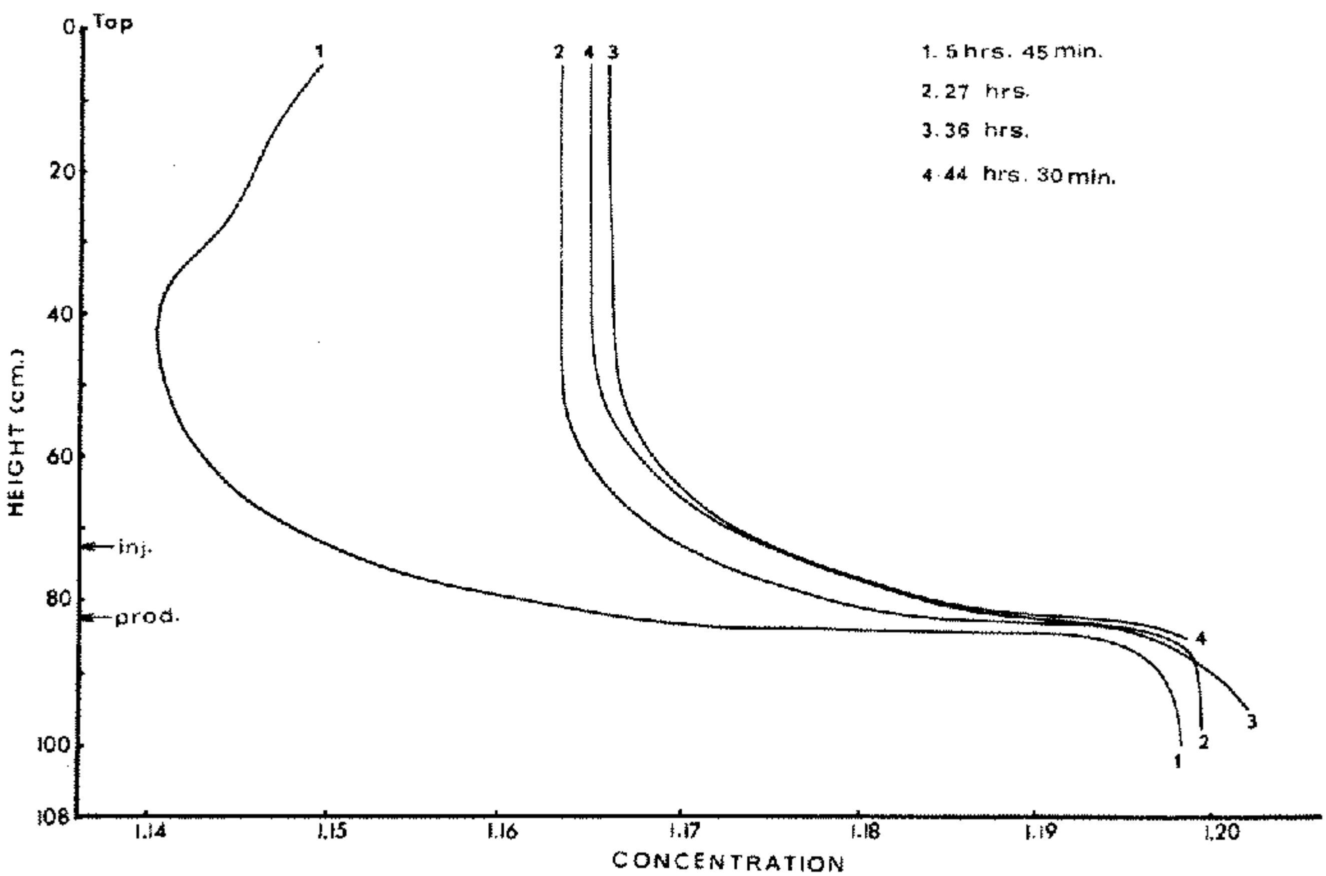

Figure 8. Concentration profile in the cavity during stage 2 (long block).

TABLE III

Input data for cavity washing in long block

Stages	Washing Time (hrs)	Injection Pipe Position (cm)*	Production Pipe Position (cm)*	Average Rated Production (cc/min)
First	4.5	21.8	11	32
Second	50.5	36	26	40

*Distance from bottom of cavity.

TABLE IV

Calculated and measured cavity volume in long block

Stages	(1) Initial Volume (cc)	(2) Calculated Volume Removed (cc)	(3) Total Volume Measured (cc)	(4) Total Volume Calculated (1)+(2)	(5) Difference (4)−(3)%
First	2209	1156	3365	3365	0
Second	3365	14585	17945	17940	Negligible

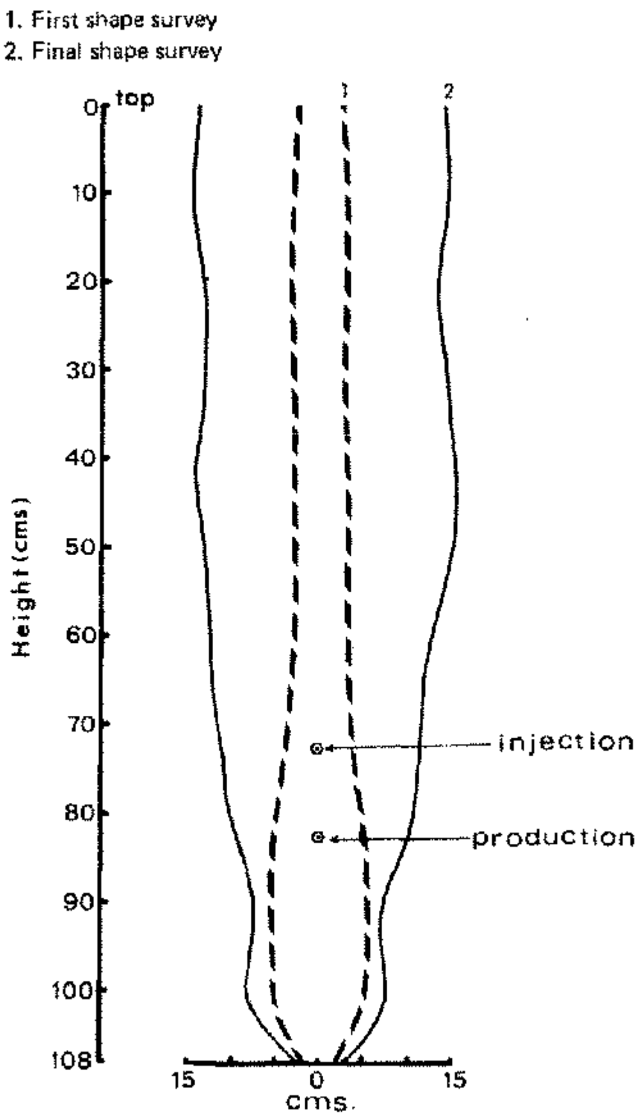

Figure 9. Measured cavity development (long block).

gradient on the cavity shape are obvious. It is believed that this phenomenon frequently occurs in the initial stages of long narrow field cavities leading to a "bottle-shaped" cavern. In later stages as the diameter widens the cavities become more cylindrical or even funnel shaped as indicated by the salinity profiles 2, 3, and 4 (Fig. 8). The shape of the model cavity after the first and second stage washing is presented in Figure 9. It should be noted that the area below a depth of 90 cm is part of the sump. Figure 10 represents a picture of the solution cavity after comple-

Figure 10. Solution cavity after completion of test (long block).

tion of stage 2 with the Lucite plate removed. It shows the typically uneven walls as well as an enlargement in the upper portion of the cavity. The latter is due to a fracture in the salt block and illustrates the influence of fractures on the shape of solution cavities.

With the help of the measured brine concentration profiles (Fig. 8) and available rate of salt removal data (Durie and Jessen 1964) the cavity shape for the respective time intervals were calculated. The calculated cavity development is plotted in Figure 11. The greatest discrepancy between the measured and calculated final cavity shape occurs at the top where it was approximately 8%. Part of this error must be attributed to the fact that the last salinity profile was determined 6 hours prior to termination of the test. Further details are presented elsewhere (Progress Report, December 1, 1972).

CONCLUSIONS

Model solution cavities using single well systems were washed in massive (non-stratified) salt blocks. The tests were initiated to study the effect of the injection pipe position and the cavity height on the salinity distribution in the bulk fluid. The production pipe was located at the bottom of the cavity at all times. The tests indicated that the salinity distribution in the bulk fluid of the cavern is very sensitive to the injection pipe position. From the point of view of cavern roof stability it was found that top injection led to an undesirable cavern geometry since most of the salt dissolution occurred at the top. Because of the geometry a cavity might have to be abandoned prematurely leading to a low salt recovery. Near bottom injection will lead to a more cylindrically shaped cavity. This is particularly important for seam like deposits with limited height. Here the short distance that fresh water can rise will lead to incomplete mixing of the water-brine system. In these cases jet injection (cf. von Schonfeldt and Remolina, 1974) at the bottom of the cavity should be considered to obtain a more stable initial cavity shape. The tests also showed that an inversion of the salinity distribution might occur in the initial stages leading to "bottle" shaped caverns. It was also shown that accurate cavity shape predictions may be made if the salinity gradient in the cavern is known.

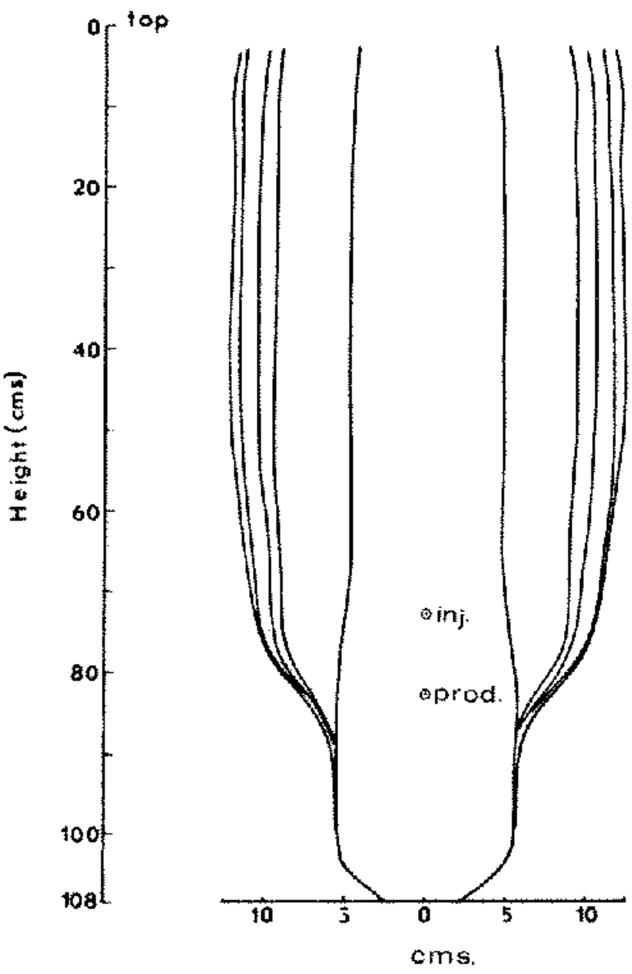

Figure 11. Calculated cavity development.

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