Mechanism of Solution and Cavity Control in a Two-Well System with Emphasis on Jetting

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ABSTRACT

Model cavity washing experiments with two well systems were carried out in a salt block measuring 50 cm X 70 cm X 70 cm. The objective of the tests was to determine the effect of borehole inclination and jetting on the cavity development; of particular interest was the influence of these parameters on the way communication between the two wells was established. The results showed that in both cases more stable initial cavity shapes could be obtained and that jetting the injection water horizontally into the cavities was an effective means of connecting two neighboring wells.

INTRODUCTION

In solution mining, considerable research has been undertaken to investigate the fundamental aspects of the dissolution of salt and the development of cavities of different shapes.

Stability and volume of cavities are of major concern to the solution mining industry. This study deals with the problem of forming large stable cavities on a laboratory scale by using inclined boreholes and "jet" injection. The latter technique is used to join two cavities in order to obtain a bigger one.

Joining cavities in a two-well system has been achieved in the laboratory by two different methods. One is accomplished by using fractures (Meyer, 1970) and the other by controlling an inert blanket fluid level (Arslan, 1970). The former has limitations by the difficulty of controlling the extent and direction of the fracture; the latter is limited by problems that occur in the control of the inert blanket fluid level.

The present study is divided into two experiments. The first one was undertaken to determine the effect of a moderate borehole inclination on the final cavity shape in a two-well system. The second test was conducted under similar conditions, except that the water was injected horizontally into the cavity through an orifice. Although this does not represent a jet, the term, jetting, will be used frequently to describe injection through an orifice. While there appears to be little information available concerning the associated flow problem around an orifice, Durie and Jessen (1964) investigated the effect of the angle of inclination on the salt removal rate. Both cases where water overlies the salt face (positive inclination) and where water underlies the salt face (negative inclination) were considered. Based on theoretical and experimental results, they concluded that salt dissolution at a given bulk fluid concentration occurred at a faster rate for the case of negative inclination of the salt face. The highest rate of salt removal took place when the salt face was oriented horizontally over the water. Some of their conclusions will apply to the present study.

PREPARATION OF THE SALT BLOCK

A salt block, measuring approximately 50 cm X 70 cm X 70 cm was chosen for the experiments. A large fracture traversed the block diagonally; the parts on either side, however, appeared to be intact. It was decided to run one test in each of these unfractured portions. The salt contained approximately 6% to 7% anhydrite distributed homogeneously throughout the block.

Two wells, 10 cm apart for the first experiment, and 11 cm apart for the second one, with a diameter of 1.27 cm each, were drilled to a depth of 40 cm in each of the intact portions. Both holes were drilled inclined to the vertical, at an angle of approximately 12°. The top part of each hole was enlarged to a diameter of 6.0 cm for the first, and 6.5 cm for the second test, to a depth of 7.5 cm in order to accommodate the well head. After the head was cemented into the enlarged hole, the block was covered with several coats of epoxy (Hysol) to prevent any leakage during the experiment. For the second experiment, the wellhead was removable in order to be able to pass sonar survey equipment into the cavity (see below).

Injection, production and the control of the inert blanket fluid was accomplished by means of three concentric tubes fitted into the wellhead.

EXPERIMENT NO. 1

The main objective of the first experiment was to study the effects of inclined boreholes on the development and the final shape of a cavity in a two-well system.

Procedure

The cavity washing was conducted in three separate stages. During the first stage, a sump was constructed for each borehole to hold the insolubles; in the second stage, the two independent cavities were joined and in the third stage, the cavities were operated as a single two-well system by injecting through one well and producing through the other one. The sumps for each of the wells were washed in direct circulation while the remaining two stages were washed in reverse circulation. The respective inside diameters of the production, injection, and blanket fluid tubings were 0.318 cm, 0.954 cm, and 1.59 cm. After completion of the sumps the two wells were operated simultaneously and independently until communication was established.

Kerosene was introduced through the outer annulus as a blanket fluid, such that the total height of salt exposed was 23.5 cm in each hole. As the cavity developed, kerosene was added periodically to maintain the level at the desired point. The effluent was collected, and the specific gravity measured every 30 minute period throughout the run. From these data the salt removed was calculated. In addition, the cavity volume was determined by filling up the cavity with saturated brine.

During the final phase of this test, fresh water was injected through well No. 1 at a rate of 33 cc/min, and the brine was produced through well No. 2. The blanket fluid level was maintained at the same point as in the previous stage so that no variation in the total height of exposed salt occurred.

The experiment was conducted in steps of 12 to 13 hours. After each of these periods, the cavity was immediately emptied, and the process started again the next morning after the cavity was filled up with the same brine that had been taken out previously. Because of the relatively small volume of the cavity, the concentration gradient was reestablished quickly, and therefore, the effect of this process on the cavity development is considered negligible compared to a continuous process.

The controlling parameters for the first experiment are summarized in Table I.

Results

The total washing time for stage 2 and 3 was 61 hours. During this time, 14,155 cc of salt were removed from the cavity as calculated from the effluent concentration, and 1,700 cc were obtained from the brine that remained in the cavity after termination of the experiment. Thus, the total amount of salt removed from the salt block was 15,855 cc. The measured final volume of the cavity was 15,901 cc, which is in good agreement with the calculated value. Detailed production data are given elsewhere (Remolina, 1973). Table II summarizes the salt volumes removed in each stage.

Figure 1 shows the rate of production and the effluent concentration versus time for the periods before and after communication was established. Expectedly, the effluent concentration increased with time until the two cavities were joined. After that, a gradual decrease in concentration was observed, which is attributed to a decrease in surface area due to the dissolution of the salt barrier between the two cavities.

Figure 2 gives a cross-sectional view of the final cavity

TABLE II

Salt volume removed in experiments no. 1 and no. 2

Stages	Experiment No. 1		Experiment No. 2	
	Well No. 1 (cm)	Well No. 2 (cm)	Well No. 1	Well No. 2
First (sump)	532	512	557	545
Second	2,532	2,502	2,831	2,786
Third	10,819		7,692	

TABLE I

Parameters for experiment no. 1

Stages	Injection Point Each Well (cm)	Production Point Each Well (cm)	Average Rate of Injection (cc/min)	Duration of Test (hrs)	
				Well 1	Well 2
First	1 *	8*	60-130	6	4
Second	2.5**	0*	15	22.42	22.42
Third	Same	Same	33	38.58	

*Distance measured from bottom.

**Distance measured from top of sump.

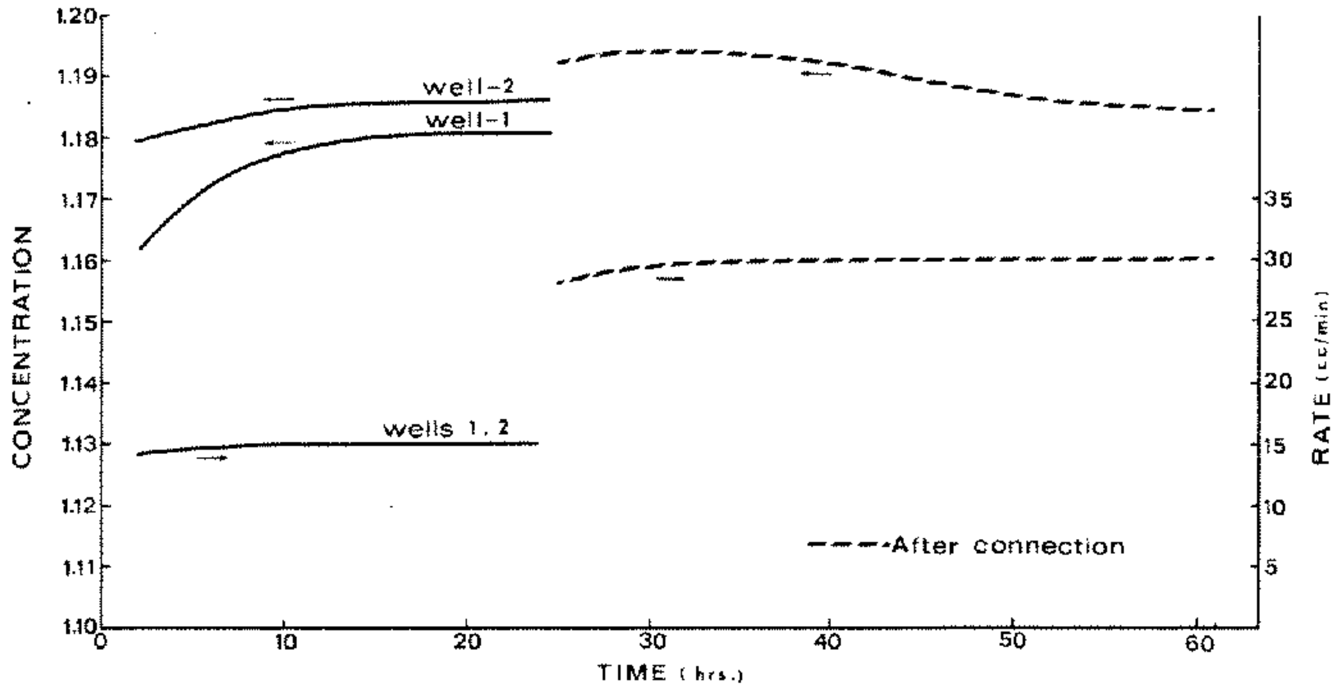

Figure 1. Rate and concentration of the effluent vs time (Experiment No. 1).

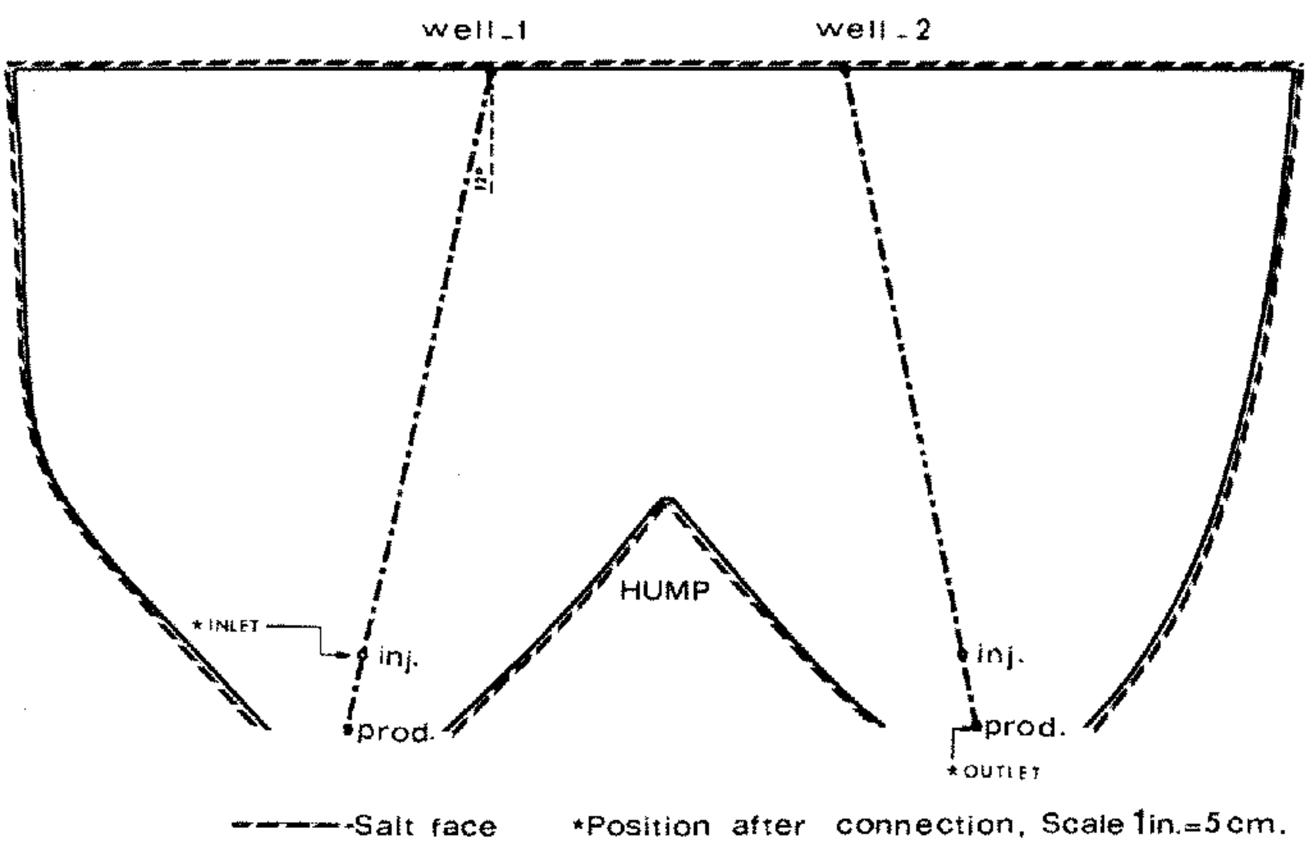

Figure 2. Measured final shape of the cavity (Experiment No. 1).

shape. This figure indicates that communication was established at the top of the cavity almost midway between the two wells. In numerous single-well model experiments of this nature with injection through a vertical pipe, "morning glory" shaped cavities were obtained. The present cavity system appears to depart from this type of behavior. As indicated in the introduction, a negative inclination of the salt face leads to a higher dissolution rate. Thus, for example, considerably more salt was dissolved to the left by well No. 1 than to the right. Because of the additional salt volume, communication between the wells was established before the typical regression at the top could take place. It is noted also that the peak of the "hump" coincides with the change in slope of the cavity wall, particularly in well No. 1. After the two wells had connected, all the brine from well No. 1 had to enter cavity No. 2 crossing the gradually receding barrier. Thus a "convection cell" probably was established, whose lower boundary coincided with the peak of the barrier. The slightly larger volume of cavity No. 1 is expected since in stage 3 all the fresh water was injected through this well, leading to a higher dissolution there.

EXPERIMENT NO. 2

The objective of this experiment was to study the effect on the cavity development in a two-well system caused by horizontal injection of water.

Procedure

Similar to the first experiment, the test was conducted in three stages: washing of sump for each well, joining the cavities, and joint operation of the two-well system.

The injection rates and the dimensions of the pipes were the same as previously. The injection pipes were sealed at the bottom and a 0.0794 cm orifice was drilled laterally into the pipe. With the given rates of 15 cc/min and 30 cc/min for stage 2 and stage 3, the respective average exit velocities were 51 cm/sec and 102 cm/sec. During stage 2 the jets were directed towards each other (Fig. 4). After communication between the wells was established, fresh water was injected through well No. 2 (Fig. 4) at a rate of 30 cc/min, and the brine was produced through well No. 2. The injection and production wells were reversed after 18.25 hours and the system was operated this way for an additional 7 hours. The level of blanket fluid (kerosene) was kept constant at a height such that 24.8 cm of salt was exposed to solution. Table III summarizes the controlling parameters for experiment No. 2.

Determination of the cavity shape

In order to determine the effect of this particular injection system on the development of the cavity shape, four shape surveys were carried out at different times during the total time of washing. Two were made before, and the other two after communication was established between the two wells. The method utilized the sonar principle to determine the distance between the wellbore and the cavity wall. Details are given elsewhere (Remolina, 1973).

Results

The total time of washing for this experiment was 52 hours, excluding the washing time for the sumps. The volume of salt calculated from the effluent concentration was 11,443 cc, and 1,776 cc were obtained from the brine in the cavity. Thus, the total volume of salt removed was 13,209 cc, which is in good agreement with the measured final volume of 13,300 cc. Detailed production data are given elsewhere (Remolina, 1973). The removed salt volume in each stage as calculated from the effluent concentration is summarized in Table II.

As illustrated by Figure 3, the rate of production remained reasonably constant within each period. The concentration of the effluent plotted as a function of time is also given. Figure 4 illustrates the cavity shape development during the various stages of washing. It shows clearly that the cavities established communication midway between wells at a height slightly above the injection point. The shape surveys also show that more dissolution took place at the height of the injection point all around the cavern. This is thought to be due to a better mixing and circular movement in this zone caused by the jet.

A preliminary analysis of the jetting action was based on Albertson (1950). He suggested that the maximum velocity in the jet stream decreases as $1/x$, where x is the horizontal distance measured from the jet along the flow path. The analysis indicated that the effect of the orifice injection at a rate of 15 cc/min subsided at a distance approximately halfway between well No. 1 and well No. 2. Although this analysis neglected the effect of the buoy-

TABLE III

Parameters for experiment no. 2

Stages	Injection Point Each Well (cm)	Production Point Each Well (cm)	Average Rate of Injection (cc/min)	Duration of Test (hrs)
First	1 *	8*	70-95	5.28
Second	2.5**	0*	15	26.75
Third	Same	Same	30	25.25

*Distance measured from bottom of hole.

**Distance measured from top of sump.

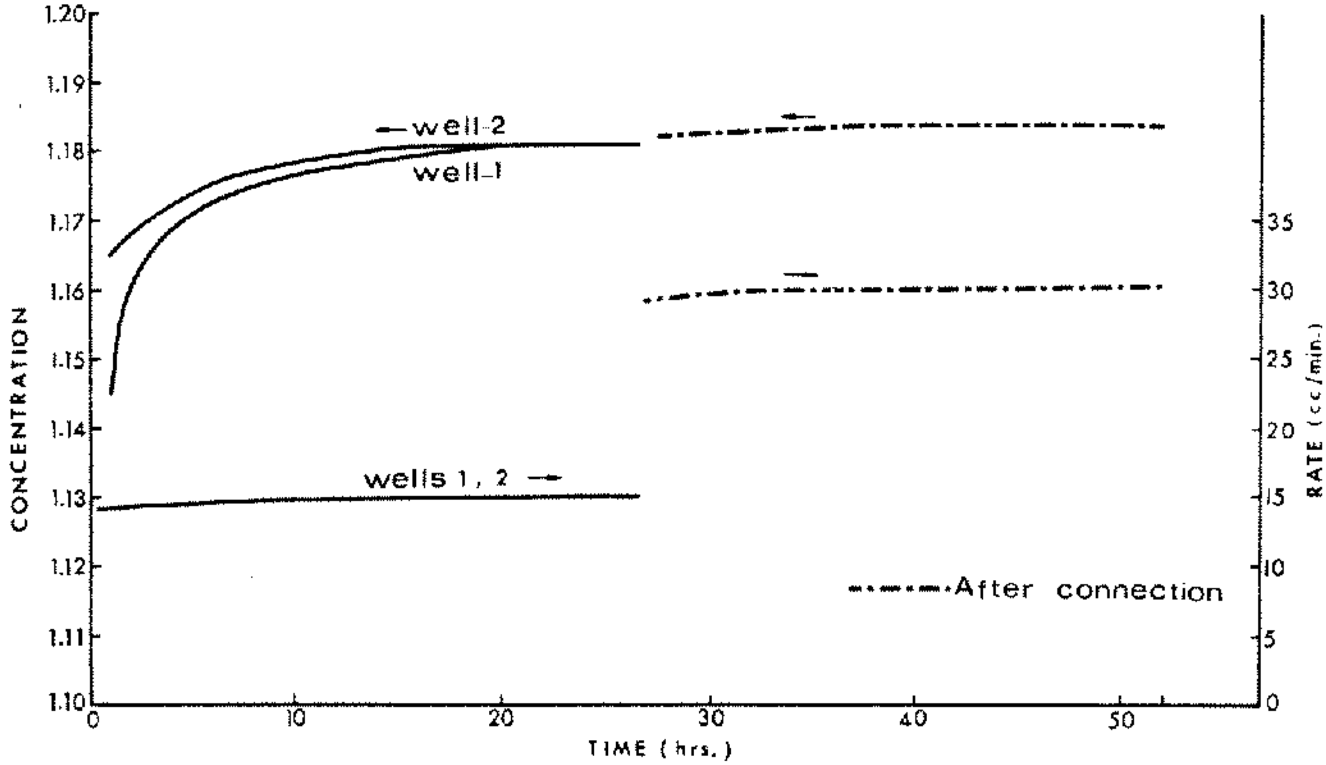

Figure 3. Rate and concentration of the effluent vs time (Experiment No. 2).

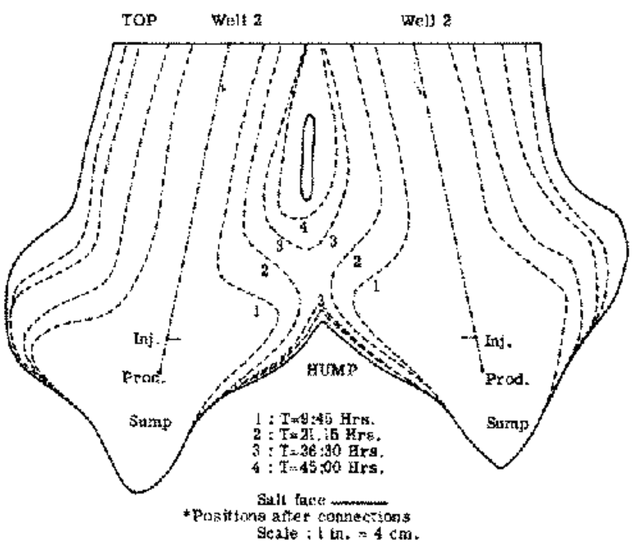

Figure 4. Ultrasonic shape surveys and final shape of the cavity (Experiment No. 2).

ancy force on the injected stream, good agreement between the experimental evidence and the predicted jetting effect was reached. Details are given elsewhere (Remolina, 1973).

It is quite obvious that the cavern in Figure 4 has a significantly more stable geometry than a "morning glory" shaped cavity. Figure 4 also illustrates that a second connection between the cavities was made after the fourth survey. It is noted, however, that no trend towards the typical regression of the salt at the top of the cavity is noticeable. This indicates the influence of jetting which directs the fresh water towards the center of the cavity system leading to rapid dissolution of the center barrier. It is believed that jetting will result in a more complete mixing of the fresh water-brine system in the lower portions of the cavity, which will lead to a more uniform and higher concentration of the brine in the upper portions of the cavity. Thus jetting will lead to a statically stabler cavity shape. After termination of the experiment, the salt block was cut, exposing half of the cavity. It is presented in Figure 5.

Figure 5. Final shape of the cavity after cutting the salt block (Experiment No. 2).

CONCLUSIONS

In the experiments described above, the effect of borehole inclination and jetting on solution mechanism and cavity development in two-well systems was studied. It was found that more stable initial cavity shapes could be obtained. Jetting the injection water horizontally into the cavities was very effective in establishing communication between two wells. Considering the uncertainty and cost of connecting neighboring wells by means of hydraulic fracturing or by means of blanket fluid control, it might be well worthwhile to further explore the potential of jetting for such purposes.

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