Solution Mining Operations in the Presence of Vertical Fracture Systems

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ABSTRACT

Data is presented on experimental models involving the use of both vertical and horizontal fractures in two-well systems in which the fractures may exist initially adjacent to an insoluble or inert bed or located with massive salt above the fracture. Results of mathematical simulation and experimental model data are presented. Different solution patterns are developed depending on the mode of fracture system. Shape of cavities formed in massive salt sections are affected more by solution at the roof surface while cavities formed in which insoluble beds appear as roof members take on the appearance which is expected from vertical surface exposure.

Introduction and purpose.

Though fracturing operations are frequently carried out in making connections between wells which are to be used in developing brine production, rather limited information is available on the effect of orientation of the fracture plane. Numerous authors (Bays, Peters and Pullen, 1960; Shock, 1965; Shock and Davis, 1969) have presented data on fracturing techniques for use in salt solution mining operations, and recently Davis and Shock (1969) reported results of mining thin bedded potash salt beds exposed by horizontal fracture planes. With the advent of deeper and deeper exploration for minerals which may be recovered through solution mining, the probability of utilizing induced fractures becomes greater. This study was undertaken because formation of vertical fractures occurs at greater frequency with depth, and because no direct experimental evidence is available regarding the solution of salt in such fractures.

Experimental work.

The experimental work involved use of solid salt blocks obtained from the Grand Saline, Texas, mine of Morton Salt Company and from the United Salt mine at Hockley, Texas. In the case of the test in which an insoluble bed above the fracture was simulated, a cut approximately 1-2 mm in thickness was made with a saw into a previously smoothed face. Depth of the simulated fracture was 2 1/2 inches, and its length was 14 1/2 inches. After sealing a 1/4-inch Lucite sheet to the salt surface with Hysol, the whole block was sealed, with the same material, in a wooden frame so as to assure no leakage during the test period. Inlet and outlet wells were drilled through the Hysol seal and Lucite plate. All cuttings, including a small amount of salt, were removed by jetting with high pressure air.

The washing system was comprised of two needle valves and a pressure regulator to control the rate of flow of water, a calibrated rotameter to measure the volume of inlet water, and several large cylinders to measure the volume of effluent. Specific gravity of the brine was determined with hydrometers.

In order to eliminate air from the system an inverted Tee was placed in the feed water line at the highest elevation. Thus, any air which might be trapped in the salt cavity being formed during washing could be removed by turning the whole salt block over and allowing air to rise through the flexible nylon wash tubing and be expelled.

The washing procedure was started by filling the fracture with water while the salt block was oriented in an upright position. The air present was removed. Next, the block was placed in a flat position with the inlet and outlet tubes at the top. Then, if no air bubbles could be seen in the flow stream, the block was inverted. Water now entered the bottom of the fracture and was produced from the bottom. Washing was continued in this manner, and readings were made every 15 minutes of the volume, rate, specific gravity of effluent, and amount of solids. The solids, consisting of fine anhydrite crystals, were removed when it appeared flow was impeded. This occurred only once with this particular salt block which contained only 1-2 percent insoluble material. Some small amounts of water from the cavity were lost during such an operation, but since these volumes were small in comparison with the total volume of water measured or salt removed was introduced.

Data for this test are shown in Table 1. A cavity with a total volume of 3835 cc was formed. Time of washing was 717 minutes (approximately 12 hours). The rate of flow was decreased from an initial value of 200 cc per minute to an average of 45-50 cc per minute after the first 45 minutes of circulation. The specific gravity of the effluent increased from 1.082 to 1.164 after about 1 hour and 15 minutes and remained at near this saturation for the next 5 hours and 45 minutes. The saturation of the effluent then decreased and the specific gravity remaining fairly constant at 1.115 during the last 4 hours and 45 minutes. The average flow rate during this time was 50 cc per minute whereas that during the previous 5 hour 45 minutes leaching was 44 cc per minute. There appears to be a direct relationship between the circulation rate and the saturation of effluent, indicating control of the development of the cavity was related to the rate of flow, since at no time was the effluent brine saturated. In other words, though there was an ever-increasing surface exposed to attack, which should have provided greater solution of salt based on previous studies of solution rates in single well systems, (Durie and Jessen, 1964) the flow mechanism was such that a lesser efficiency of salt removal resulted. Thus a maximum width to depth (or heigth of fracture) ratio probably exists for commercial utilization in mining rather thin beds by solution techniques.

The final cavity shape is shown in Figure 1 whereas the progression with time is indicated in Figure 2. From a consideration of Figure 1 the volume may be expressed as

$$V = 2/3\ y\ a\ h - 2/3\ a\ x\ (h - b)$$

or

$$V = 2/3\ a\ b\ (x + y) \qquad (1)$$

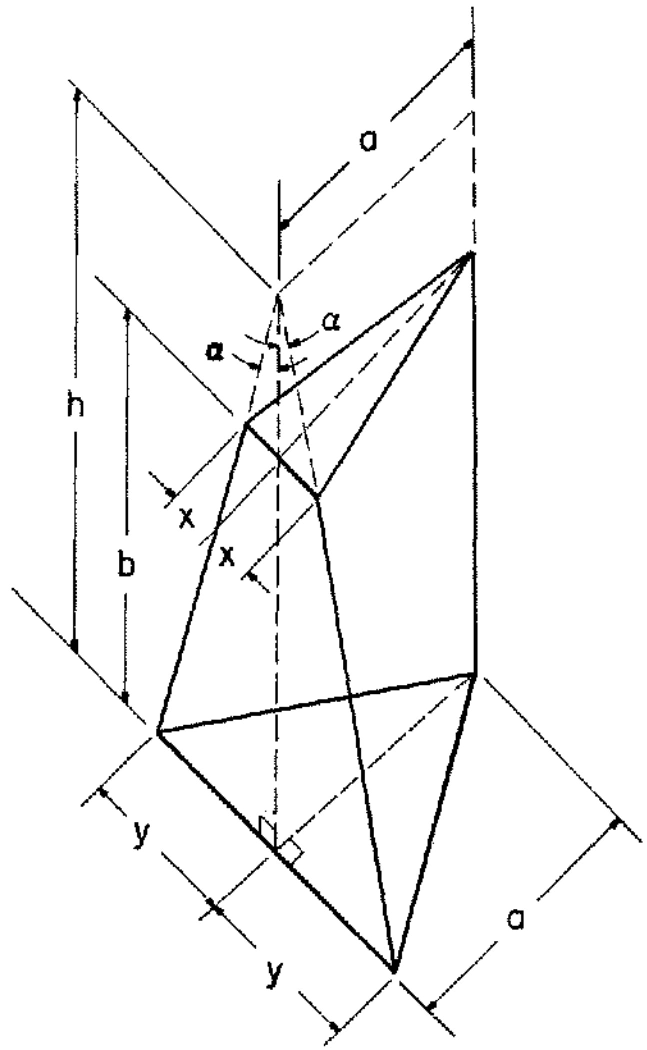

Figure 1. Insoluble bed above the fracture.

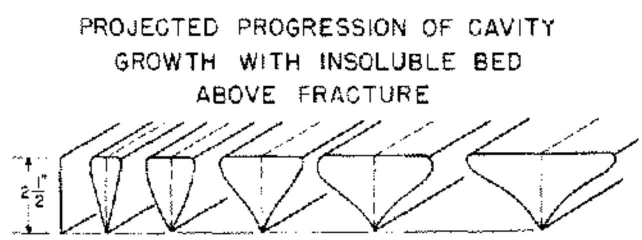

Figure 2.

Substituting the corresponding values of a, b, x, and y at the end of the test into Equation 1 results in a value of

$$V = 2/3 \times 2\ 1/2 \times 16\ (5\text{-}3/8 + 4\ 1/8)$$

$$V = 261.25 \text{ cubic inches, or}$$

$$V = 4281 \text{ cubic centimeters.}$$

Table 1. Washing Data For Vertical Fracture Impermeable Bed Above Fracture

Source of Salt: Grand Saline Mine
Morton Salt, Co., Grand Saline, Texas

Initial Fracture Length = 13 inches
Initial Fracture Width = 3 mm
Initial Fracture Depth = 2 1/2 inches

Time Interval Minutes	Volume of Water cc		Flow Rate cc/Minute	Specific Gravity Effluent	Salt Removed cc/Stage	Cumulative Volume of Cavity cc
	Per Time Interval	Cumulative				
8.5	1,700	1,700	200.	1.082	91.4	91.4
4.0	800	2,500	200	1.1	57.6	149.0
5.0	640	3,140	128	1.107	30.2	179.2
5.0	640	3,780	128	1.121	32.5	211.7
5.0	640	4,420	128	1.128	32.4	244.1
5.0	670	5,090	134	1.128	34.9	279.0
5.0	640	6,730	128	1.126	34.8	313.8
13.0	1,750	8,480	134	1.122	138.0	451.8
7.8	390	8,870	50	1.121	30.2	482.0
8.0	400	9,200	50	1.130	32.1	514.1
8.0	345	9,545	43	1.144	31.7	545.8
12.0	490	10,035	40	1.160	48.1	594.9
5.0	180	10,285	36	1.170	19.35	604.3
10.0	445	10,730	44.5	1.173	47.5	651.8
10.0	390	11,120	39.0	1.172	42.2	694.0
13.0	425	11,545	32.3	1.176	46.7	740.7
10.0	490	12,035	49.0	1.175	53.7	794.4
10.0	420	12,455	42.0	1.170	44.99	839.3
10.0	465	12,920	46.5	1.165	47.7	887.0
10.0	360	13,280	36.0	1.170	38.5	925.5
12.0	360	.3,640	30.0	1.176	35.3	960.8
15.0	650	14,290	43.0	1.172	69.2	1,030.0
15.0	600	14,890	40	1.170	64.0	1,094.0
15.0	780	15,670	54	1.162	83.0	1,177.0
15.0	780	16,450	54	1.156	76.8	1,253.8
15.0	700	17,100	48	1.158	70.0	1,323.8
15.0	780	17,880	52	1.155	76.5	1,400.3
15.0	730	18,610	48.5	1.154	71.0	1,471.3
15.0	685	19,295	45.7	1.154	66.8	1,538.1
15.0	650	19,945	43.3	1.156	64.0	1,602.1
15.0	600	20,545	40.0	1.158	59.75	1,661.85
15.0	700	21,245	46.7	1.158	68.2	1,730.0
15.0	650	21,895	43.3	1.148	64.0	1,794.0
5.0	200	22,095	40.0	1.188	23.7	1,817.7
32	1,640.0	23,735	51.0	1.170	174.5	1,992.2
13.0	640.0	24,375	50.0	1.144	58.35	2,050.5
15.0	570.0	24,945	38.0	1.14	51.5	2,102.0
7.0	760.0	25,705	110.0	1.119	58.5	2,160.5

Time Interval Minutes	Volume of Water cc Per Time Interval	Volume of Water cc Cumulative	Flow Rate cc/Minute	Specific Gravity Effluent	Salt Removed cc/Stage	Cumulati Volume of Cavity cc
8.0	560.0	26,265	70.0	1.125	45.2	2,205.7
15.0	650.0	26,915	43.0	1.138	57.5	2,263.2
15.0	770	27,685	51.0	1.142	70.0	2,333.2
15.0	640	28,325	42.0	1.144	58.5	2,391.7
15.0	855	29,180	57.0	1.136	75.3	2,467.0
15.0	1,420	30,600	94.	1.12	110.5	2,677.5
15.0	985	31,585	65.6	1.107	68.5	2,746.0
15.0	870	32,455	58.0	1.110	61.5	2,807.5
15.0	835	33,290	55.6	1.113	60.7	2,868.2
15.0	790	34,080	52.6	1.115	58.7	2,926.9
15.0	770	34,850	51.3	1.114	57.0	2,983.9
15.0	785	35,635	52.2	1.113	57.5	3,041.4
15.0	660	36,295	44.0	1.115	49.0	3,090.4
15.0	640	36,935	42.6	1.114	47.4	3,137.8
15.0	605	37,540	40.3	1.122	47.7	3,185.5
15.0	620	38,160	41.3	1.123	48.5	3,234.0
15.0	685	38,845	45.6	1.123	54.2	3,290.2
15.0	635	39,480	42.3	1.123	50.5	3,340.7
15.0	645	40,125	43.0	1.123	55.0	3,395.7
	Removed 4050 cc of saturated brine; specific gravity =			1.198	442.0	
				Total		3,837.7

The total volume recovered through washing was 4050 cc, representing a difference of 231 cc, or an error of 5 percent in calculated and observed volumes. The fact that the model assumes solution to take place on the slanting side to the very bottom of the fracture depth should result in a somewhat higher volume. As may be seen from Figure 3, final

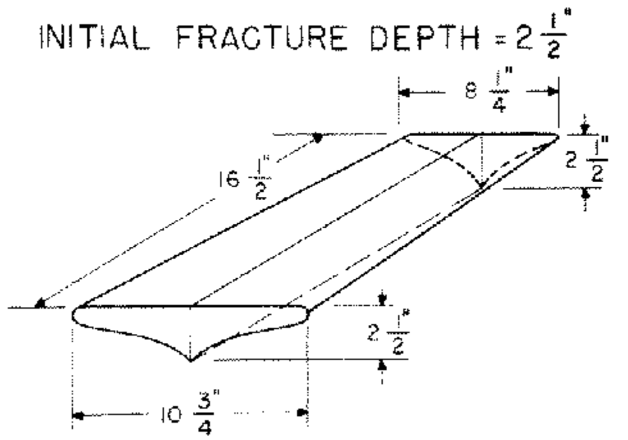

Figure 3. Final cavity shape.

shape of the washed cavity reveals the lower po tion of the initial vertical fracture still in existenc In view of this, agreement of the calculated an observed volumes is excellent.

For the case in which a vertical fracture formed in massive salt, resulting in a syste wherein soluble material exists above the top c the fracture plane, the salt block was sawed, Lucite 1/4" thick plate sealed to the cut surfac and again the entire block sealed into a woode box with Hysol. The particular salt specimen wa 12 inches wide, 24 inches long by 10 inches higl The cut was made 3 inches deep and the well spa ing was 18 1/2 inches. Preparation for leachin operations was identical with that previously de scribed except that provision was made to remov accumulated solid material by installing a glass Te section just below the entrance of the water to th injection well. By inverting the entire block, flui entry and production were at the bottom of th fracture.

The washing of this salt fracture system was co tinued for 18 1/2 hours during which a total c 75,582 cc of water was circulated and a cavity ha ing a total volume of 9160 cc was formed. Solids (anhydrite) withdrawn during the experiment and at the end of the run amounted to 812 cc.

This volume is included in the total cavity volume. Rate of flow was adjusted so that only partially saturated brine was produced. The specific gravity of the effluent during the first 6 hours and 40 minutes averaged 1.125 (67-70 percent saturation) while during the remainder of the test the corresponding values averaged 1.165, i.e., 87 percent saturation. Nearly saturated brine was produced at the end of the run. The data are tabulated in Table 2.

Projected progression of the cavity shape is shown in Figure 4 while the final configuration obtained is represented in Figure 5. It is immedi-

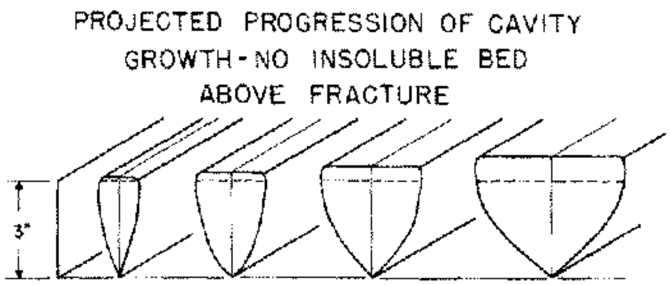

Figure 4.

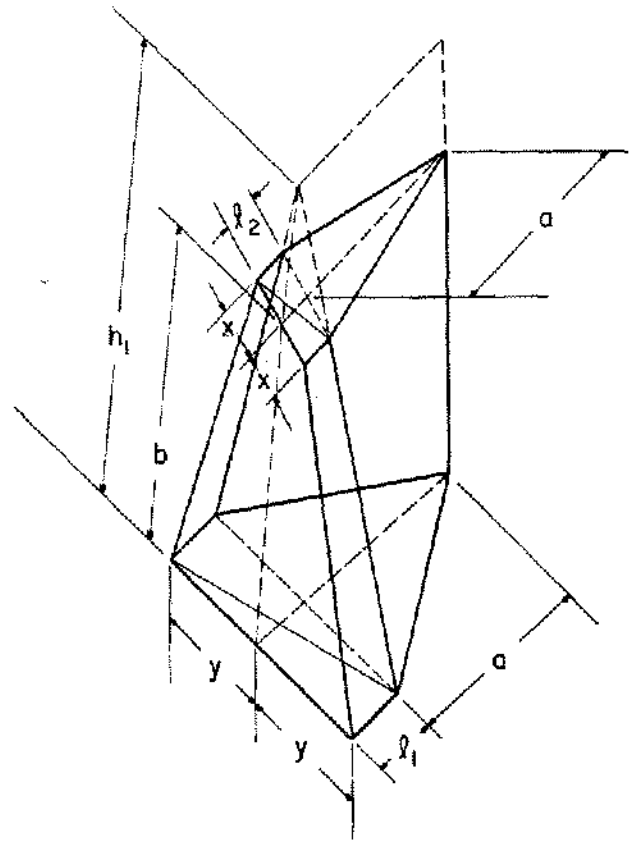

Figure 5. With soluble bed above the fracture.

ately apparent that the two shapes developed, Figure 1 and Figure 5, are similar only to the degree that both have a triangular section. Figure 5 shows the growth of the cavity also in the exposed "roof" area while this growth is denied the cavity wherein an impermeable layer overlies the vertical fracture, i.e., where the fracture terminates in an insoluble bed.

Using the same analytical approach to calculate the volume of cavity formed, the simplifying assumption is made that the progression is defined by two sections, the upper one that of a rectangle, the lower part that of a triangle. This leads to the geometric representation of Figure 6. In this case, the volume may be expressed as,

$$V = \frac{2}{3}ab(x+y) + \frac{2}{3}\left[\frac{1}{2}\sqrt{l_1^2 + 4y^2}\; h_1 \left(\frac{2l_1\, y}{\sqrt{l_1^2 + 4y^2}}\right)\right]$$

$$-\frac{2}{3}\left[\frac{1}{2}\sqrt{l_2^2 + 4y^2}\;(h_1 - b)\left(\frac{2l_2\, x}{\sqrt{l_2^2 + 4x^2}}\right)\right]$$

$$V = \frac{2}{3}ab(x+y) + \frac{2}{3}\left[l_1\, y\, h_1 - (h - b)\, l_2\, x\right]$$

h_1 can be derived, since

$$\frac{\sqrt{l_2^2 + 4x^2}}{\sqrt{l_1^2 + 4y^2}} = \frac{(h_1 - b)}{h_1}$$

or

$$h_1 = \frac{\sqrt{l_1^2 + 4y^2}}{\sqrt{l_1^2 + 4y^2} - \sqrt{l_2^2 + 4x^2}} \cdot b$$

Table 2. Washing Data For Vertical Fracture Ending In Massive Salt

Source of Salt: United Salt Company Mine
Hockley, Texas

Initial Fracture Length = 18 1/2 inches
Initial Fracture Width = 3 mm
Initial Fracture Depth = 3 inches

Time Interval Minutes	Volume of Water cc Per Time Interval	Volume of Water cc Cumulative	Flow Rate cc/Minute	Specific Gravity Effluent	Salt Removed cc/Stage	Cumulative Volume of Cavity cc
15.0	1,400	1,400	93.33	1.10	91.5	91.5
15.0	1,315	2,715	87.66	1.105	91.4	182.9
15.0	1,120	3,835	76.66	1.166	84.5	267.4
15.0	975	4,810	65.0	1.126	79.1	346.5
15.0	1,020	5,830	68.0	1.126	83.1	429.5
15.0	1,015	6,845	67.7	1.125	82.0	511.5
15.0	1,010	7,855	67.3	1.125	82.0	593.5
15.0	1,000	8,853	66.7	1.126	81.5	675.0
15.0	977	9,832	65.1	1.127	79.7	754.7
15.0	940	10,772	62.60	1.170	100.6	855.3
15.0	1,015	11,787	67.66	1.133	86.4	941.3
15.0	1,090	12,877	72.66	1.126	88.5	1,030.8
30.0	1,920	14,799	64.0	1.126	156.0	1,186.2
15.0	1,050	15,847	70.0	1.125	84.9	1,271.0
15.0	1,050	16,897	70.0	1.125	84.9	1,356.0
15.0	955	17,852	63.66	1.125	76.5	1,432.5
15.0	880	18,732	58.66	1.100	57.7	1,490.2
15.0	880	19,612	58.66	1.060	35.45	1,525.6
15.0	1,020	20,632	68.0	1.125	82.3	1,607.9
15.0	980	21,612	65.3	1.127	81.0	1,688.9
30.0	2,270	23,880	75.6	1.134	195.2	1,884.1
15.0	1,030	24,912	68.33	1.137	90.6	1,974.7
15.0	930	25,842	62.0	1.137	82.0	2,056.7
15.0	1,030	26,872	69.5	1.137	97.0	2,153.7
10.0	720	27,592	72.0	1.260	86.8	2,240.5
15.0	1,420	29,012	94.66	1.156	140.0	2,380.5
15.0	1,460	30,462	97.30	1.173	154.0	2,534.5
15.0	1,200	31,662	80.0	1.154	123.0	2,658.3
15.0	830.0	32,492	55.3	1.144	76.2	2,734.5
15.0	1,180	33,672	78.6	1.139	106.0	2,840.5
15.0	1,000	34,672	66.6	1.134	86.5	2,927.0
15.0	1,200	35,872	80.0	1.154	116.5	3,043.5
15.0	1,440	37,312	96.0	1.152	138.5	3,182.0
15.0	1,360	38,672	90.6	1.144	121.5	3,303.5
15.0	1,175	39,847	78.3	1.142	106.2	3,409.7
15.0	1,350	41,197	90.0	1.188	153.3	3,569.0
15.0	1,440	42,637	96.0	1.172	135.3	3,704.3
15.0	1,230	43,862	82.0	1.153	114.8	3,819.1
15.0	1,180	45,047	78.6	1.154	109.3	3,928.4
15.0	1,030	46,077	68.6	1.146	97.0	4,085.4

Time Interval Minutes	Volume of Water cc Per Time Interval	Volume of Water cc Cumulative	Flow Rate cc/Minute	Specific Gravity Effluent	Salt Removed cc/Stage	Cumulative Volume of Cavity cc
15.0	920	46,997	61.3	1.147	85.8	4,110.2
15.0	940	48,037	62.6	1.147	87.5	4,197.7
15.0	935	49,072	62.3	1.147	87.0	4,284.7
15.0	895	49,967	59.6	1.150	85.3	4,370.0
15.0	1,280	51,247	85.3	1.184	146.3	4,516.3
15.0	1,360	52,607	90.6	1.164	140.5	4,656.8
15.0	1,025	53,432	68.3	1.150	97.5	4,754.3
15.0	1,050	54,482	70.0	1.150	100.5	4,854.8
15.0	1,055	55,537	70.3	1.146	98.5	4,953.3
15.0	1,005	56,542	67.0	1.146	93.2	5,046.5
15.0	1,010	57,582	67.3	1.145	93.5	5,140.0
15.0	980	57,432	65.3	1.145	91.0	5,231.0
15.0	1,035	58,467	69.0	1.144	93.0	5,324.0
15.0	960	59,427	64.0	1.144	88.1	5,412.1
15.0	970	60,397	64.6	1.144	89.0	5,501.1
15.0	1,000	61,397	66.6	1.144	91.6	5,592.7
15.0	1,005	62,402	67.0	1.144	92.2	5,684.9
15.0	1,300	63,702	86.6	1.152	117.5	5,702.4
15.0	780	64,482	52.0	1.184	88.5	5,790.9
15.0	850	65,332	56.6	1.184	94.5	5,885.4
15.0	860	66,192	57.3	1.18	96.7	5,982.1
15.0	820	67,012	54.6	1.177	86.2	6,068.3
15.0	805	67,817	53.6	1.176	88.7	6,157.0
15.0	810	68,627	54.0	1.176	89.5	6,246.5
15.0	820	69,447	54.66	1.174	89.2	6,335.7
15.0	830	70,277	55.33	1.173	90.0	6,425.7
15.0	820	71,097	54.66	1.170	87.5	6,513.2
15.0	810	71,907	54.00	1.170	86.5	6,599.7
15.0	1,890	73,797	126.	1.132	145.5	6,745.2
15.0	615	74,412	41.0	1.192	72.7	6,817.9
15.0	560	74,972	34.3	1.190	63.5	6,881.4
15.0	610	75,582	40.66	1.187	71.0	6,952.4

Removed 9160 cc of saturated brine; Specific gravity = 1.2

Solids obtained during washing and at time of final evacuation of cavity = 812 cc

Total 8,929.4

Then, substituting values for the conditions at the end of the test,

h_1 = 51.765 inches l_1 = 3.0 inches a = 1.4375 inches

y = 4.875 inches l_2 = 2.5 inches

b = 21.0 inches x = 2.8125 inches

$$V = \frac{2}{3}\,[\,3 \times 4.875 \times 51.765 - 30.765 \times 2.5 \times 2.8125 + 1.4375 \times 21 \times 7.6875\,]$$

$$V = \frac{2}{3} \times 773.4155$$

V = 515.61 cubic inches,

or

V = 8449.3 cc.

The measured volume of the cavity, including the insoluble anhydrite was 9160 cc. The difference in volume, readily seen to occur because of the simplifying assumption of straight slant sides, is 711

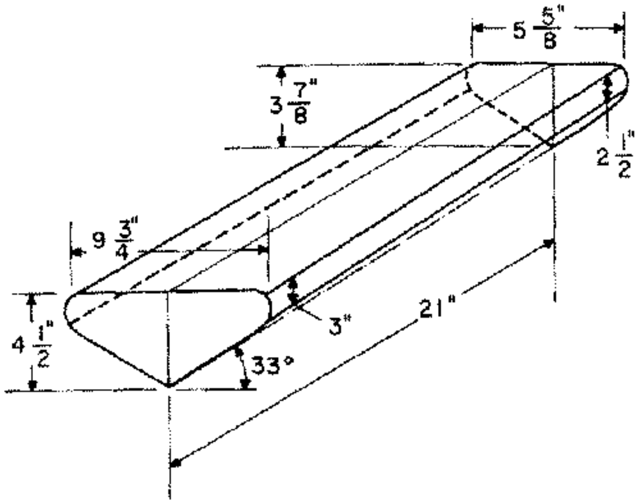

Figure 6. Final cavity shape.

cc, or 717 percent. A somewhat more rounded side results when no insoluble material is present in a salt. The photographs showing the end views of the model illustrate this point remarkably well.

To relate the change in volume with time, the data were analyzed and a curve-fit computer program, by L.N. Johnson (1969) available from the Computation Center of The University of Texas at Austin, was utilized. The general form of the equation for the volume V, as a function of time is

$$V = \frac{C_{10}}{T} + C_1 + C_2T + C_3T^2 + C_4T^3 + C_5T^4 .$$

For the case in which an impermeable bed exists immediately above the vertical fracture, the constants yield the following equation:

$$V_{(t)} = \frac{-5.48}{T} + 48.75 + 133.4T - 15.97T^2 + 2.42T^3 - 0.11T^4 .$$

Similarly, for the case where the fracture ends in massive salt,

$$V_{(t)} = \frac{-33}{T+} 133.4 + 23.8T + 17.67T^2 - 0.96T^3 + .016^4$$

where $V_{(t)}$ is the volume in $ft^3 \times 10^{-4}$

T is time in hours.

The increase in volume with time of cavities of the types formed in these experiments is shown in Figure 7. A first approximation, using only the first order term of time (T) gives a linear relationship in both instances.

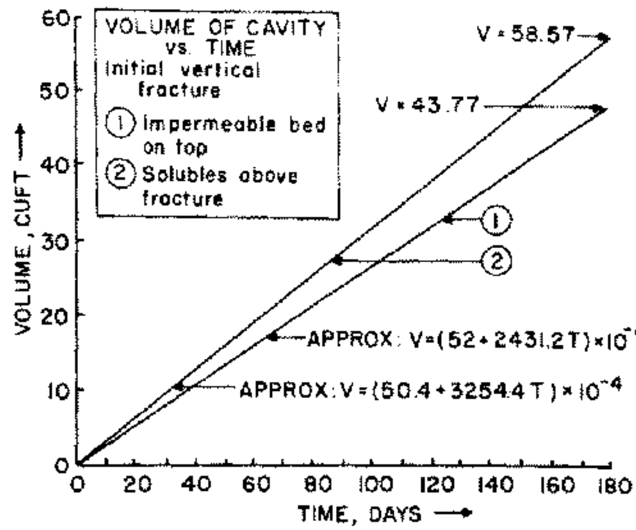

Figure 7.

Summary.

Laboratory model studies of progression of cavities in salt formed by solution in vertical fracture between two wells are reported. A triangular shaped cavity results when the solution takes place in a fracture bounded by an impermeable bed on top. There appears to be a limiting width to depth of salt bed even when little insoluble material is present. Action forms a cavity with expanding roof area and solution on the sides as solution progresses in a vertical fracture ending in massive salt. A definite limiting slope of 34 degrees of the sides results when as much as 10 percent anhydrite is present as insoluble material. Prediction of the volume of cavity formed is possible through the use of equations developed which describe the volume changes as a function of time. Proper scaling should permit utilization for developing field cavities.

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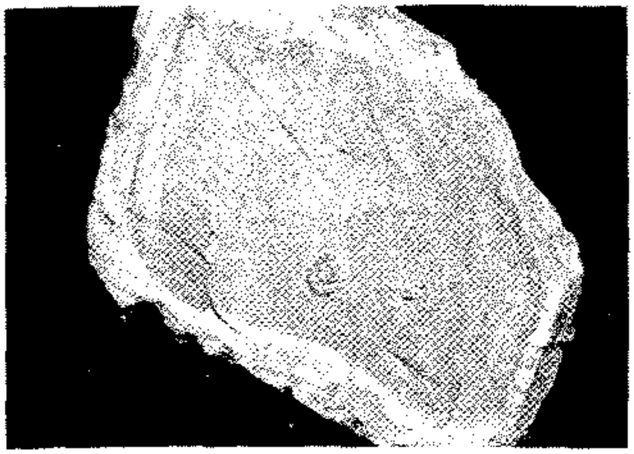
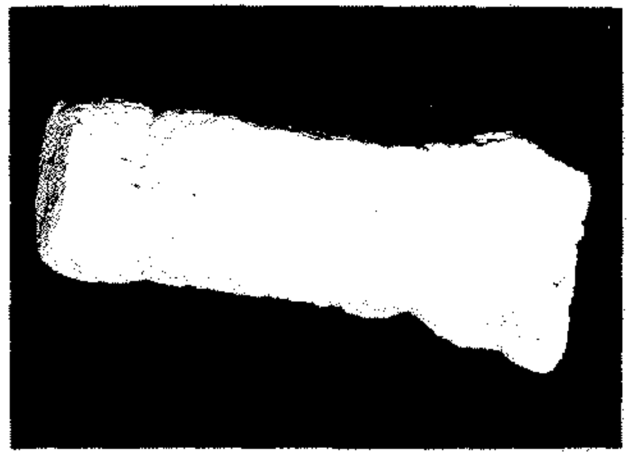
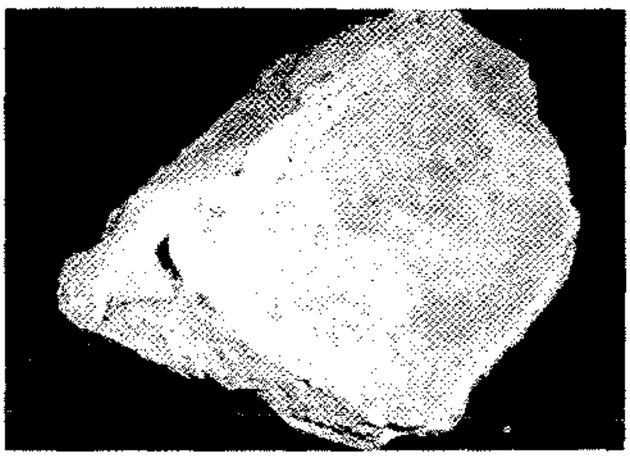


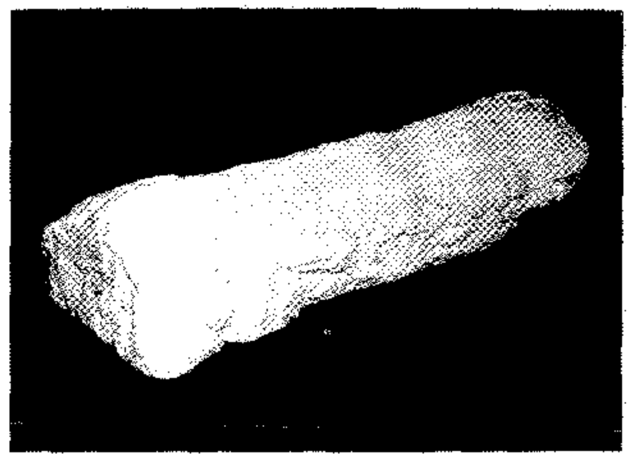
Top View, Final Cavity Impermeable bed Above Vertical Fracture



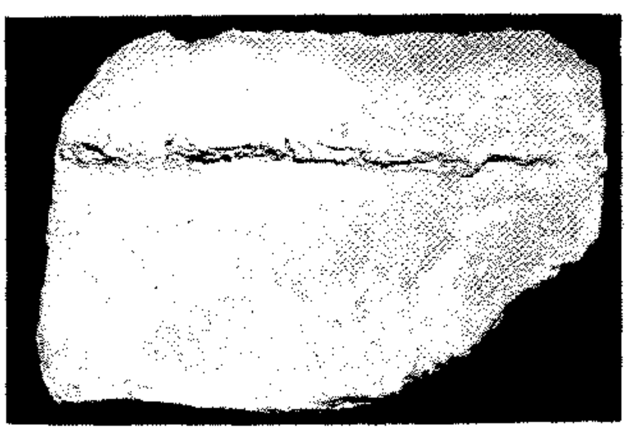
Top View of Final Cavity Vertical Fracture Ending in Massive Salt



End and Side View, Final Cavity Impermeable Bed Above Vertical Fracture



End and Side View of Final Cavity Vertical Fracture Ending in Massive Salt.



Bottom View, Final Cavity Impermeable Bed Above Vertical Fracture

Bottom View, Final Cavity Vertical Fracture Ending in Massive Salt

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