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Report of Investigations 4778

ELECTROLYTIC MODEL STUDIES AS APPLIED TO WATER-FLOODING A SHOESTRING SAND

BY WILLIAM E. ECKARD AND JACK A. MASON

United States Department of the Interior— March 1951

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UNITED STATES DEPARTMENT OF THE INTERIOR
Oscar L. Chapman, Secretary
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William E. Eckard[1] and Jack A. Mason[2]

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INTRODUCTION AND SUMMARY

Production of oil from a narrow shoestring sand presents problems unique in the oil industry. Especially important, from both an engineering and an economic standpoint, are the limitations imposed upon well patterns and spacings by the shape of the field. This report concerns a study of the Paola shoestring, Miami and Franklin Counties, Kans., where well density of 0.85 acre per well was not uncommon to insure profitable primary recovery in a reasonable time. However, such a great number of wells increased the operator's investment and reduced his profit considerably.

It was the purpose of this study to investigate various well patterns and spacings applicable to water-flooding a shoestring reservoir and the effect of these factors upon recovery of oil and the most profitable operation of the pool. The designer of well patterns for a shoestring sand should evaluate carefully the edges of the shoestring, even though they may be considered too thin to drill. These comparatively thin edges contain large quantities of recoverable oil; moreover they are resaturated with oil as the pool is water-flooded.

Several methods were used in designing the well patterns employed in this investigation. The first flooding procedure had only one stage - injection and producing wells were not changed at any time during progress of the flood. A second method involved converting producing wells to injection wells when the flood front reached an oil-producing well, or at some other specific time. A third method included drilling additional producers at some intermediate time in order to tap quantities of oil concentrated by the flood.

The electrolytic model tests indicated that the volumetric flood efficiencies of the well patterns investigated ranged from 60 to 96 percent. The most efficient flooding technique was a two-stage operation, the second stage being a modified "7-spot" pattern; development and water costs were only 19 cents per barrel of oil recovered by the operation. Well patterns 600 feet in length were 3 percent more efficient than the 500-foot patterns.

ACKNOWLEDGMENTS

This electrolytic-model investigation was made by the Bureau of Mines in cooperation with the Brundred Oil Corp. under the general supervision of R. A. Cattell, chief, Petroleum and Natural Gas Branch, Bureau of Mines, Washington, D. C., and Sam S. Taylor, supervising engineer, Bureau of Mines, Petroleum Field Office, Franklin, Pa., and under the direct supervision of E. M. Tignor, petroleum engineer, Bureau of Mines, Franklin, Pa., and R. B. Bossler, Brundred Oil Corp., Oil City, Pa.

Cooperation of the management of the Brundred Oil Corp. in furnishing the field data relative to the Paola shoestring, which made this investigation possible, is gratefully acknowledged. Special acknowledgment is made to W. J. Brundred, L. L. Brundred, B. F. Brundred, and R. B. Bossler, of the operating corporation.

Acknowledgment is made for constructive criticism of the report by H. G. Botset, head, Petroleum Engineering Department, University of Pittsburgh, Pittsburgh, Pa.; W. J. Brundred, president, Brundred Oil Corp.; R. B. Bossler, chief production engineer, Brundred Oil Corp., and consulting petroleum engineer, Bureau of Mines, Oil City, Pa.; Sam S. Taylor, supervising engineer, Bureau of Mines, Franklin, Pa.; and E. M. Tighor, petroleum engineer, Bureau of Mines, Franklin, Pa.

The illustrations used in the report were prepared by the Graphic Services Section, Central Experiment Station, Bureau of Mines, Pittsburgh, Pa.

GEOLOGY OF PAOLA SHOESTRING

The location and shape of the Paola shoestring are shown in figure 1. This pool is 8 miles long but varies in width, thickness, and shape throughout its length. The sandstone has a minimum width of approximately 300 feet and a maximum width of 600 to 700 feet. The reservoir rock of the Paola shoestring is either a sand-filled river channel or a shore feature as described by Bass.3/ The productive sand body is the Squirrel sand in the Cherokee group of Pennsylvanian age, as mentioned by Newell and Jewett.4/ Figure 1 also shows the location of the cross sections shown in figure 2.

Generally, the oil-bearing formation, which is approximately 700 feet below the surface of the ground, is thickest in the center and thins out toward both edges until it disappears. Some cross sections (fig. 2) show a thickening toward one edge, whereas others show a thin portion in the middle of the cross section and greater amounts of sandstone on both edges. The thickness of the sandstone reservoir ranges from 18 to 60 feet along the axis of the shoestring.

At the bottom of the producing formation, a zone of black micaceous sandstone from 6 inches to 12 feet in thickness sometimes is found. A high saturation of asphaltic substance is found in this black sandstone; but the asphalt-saturated sandstone is nearly impermeable, and the oil content is not recoverable by water flooding. This black sand is not separated from the oil sandstone by shale or other type of break. In the cross sections of the shoestring (fig. 2), this black sand has been omitted.

Analyses of core samples from 10 wells indicate average field conditions, as follows: porosity, 21.7 percent; permeability, 50 md; oil saturation, 49 percent; water saturation, 35 percent; oil content, 820 barrels per

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3/ Bass, N. W., Origin of Shoestring Sands in Greenwood and Butler Counties, Kans.: State Geological Survey of Kansas Bull. No. 23, Univ. of Kans. Bull. vol. 37, No. 18, Sept. 15, 1936, p. 87.

4/ Newell, N. D., and Jewett, J. M., The Geology of Johnson, Miami, and Wyandotte Counties, Kans.: State Geological Survey of Kansas Bull. No. 21, Univ. of Kans. Bull. vol. 36, No. 10, May 1935, p. 14.

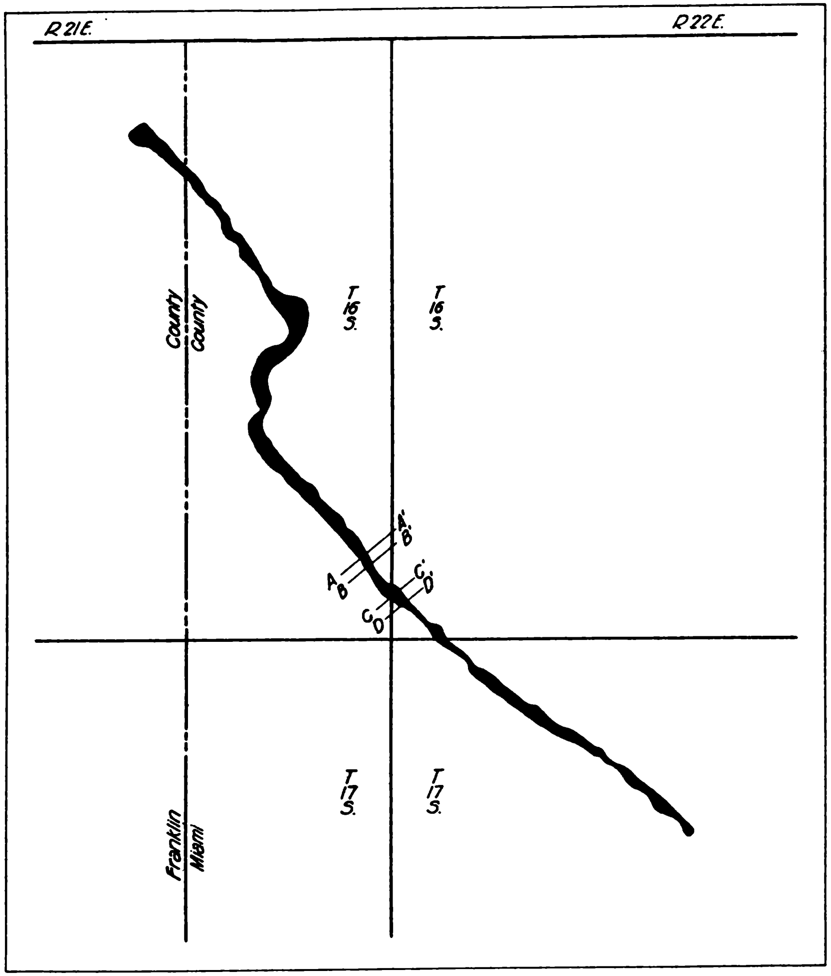

Figure I. - Paola shoestring oil field, Miami and Franklin Counties, Kans., showing location of cross sections.

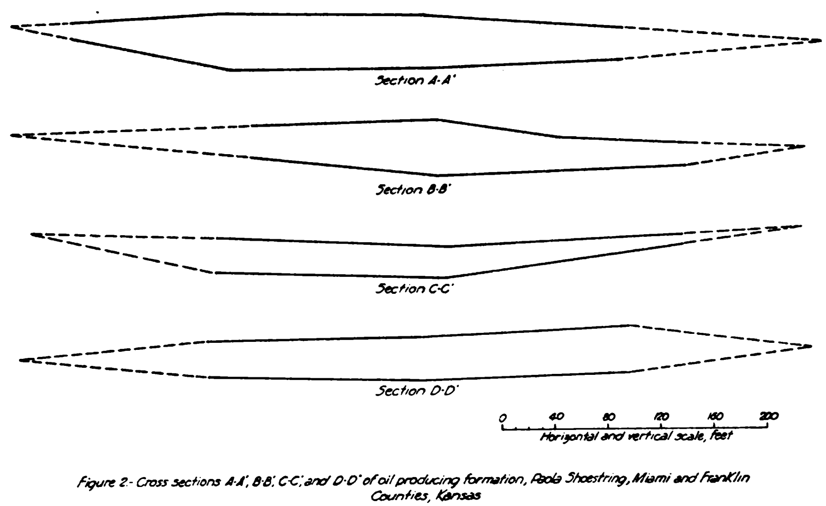

Figure 2. - Cross sections A-A', B-B', C-C', and D-D' of oil-producing formation, Paola shoestring, Miami and Franklin Counties, Kans.

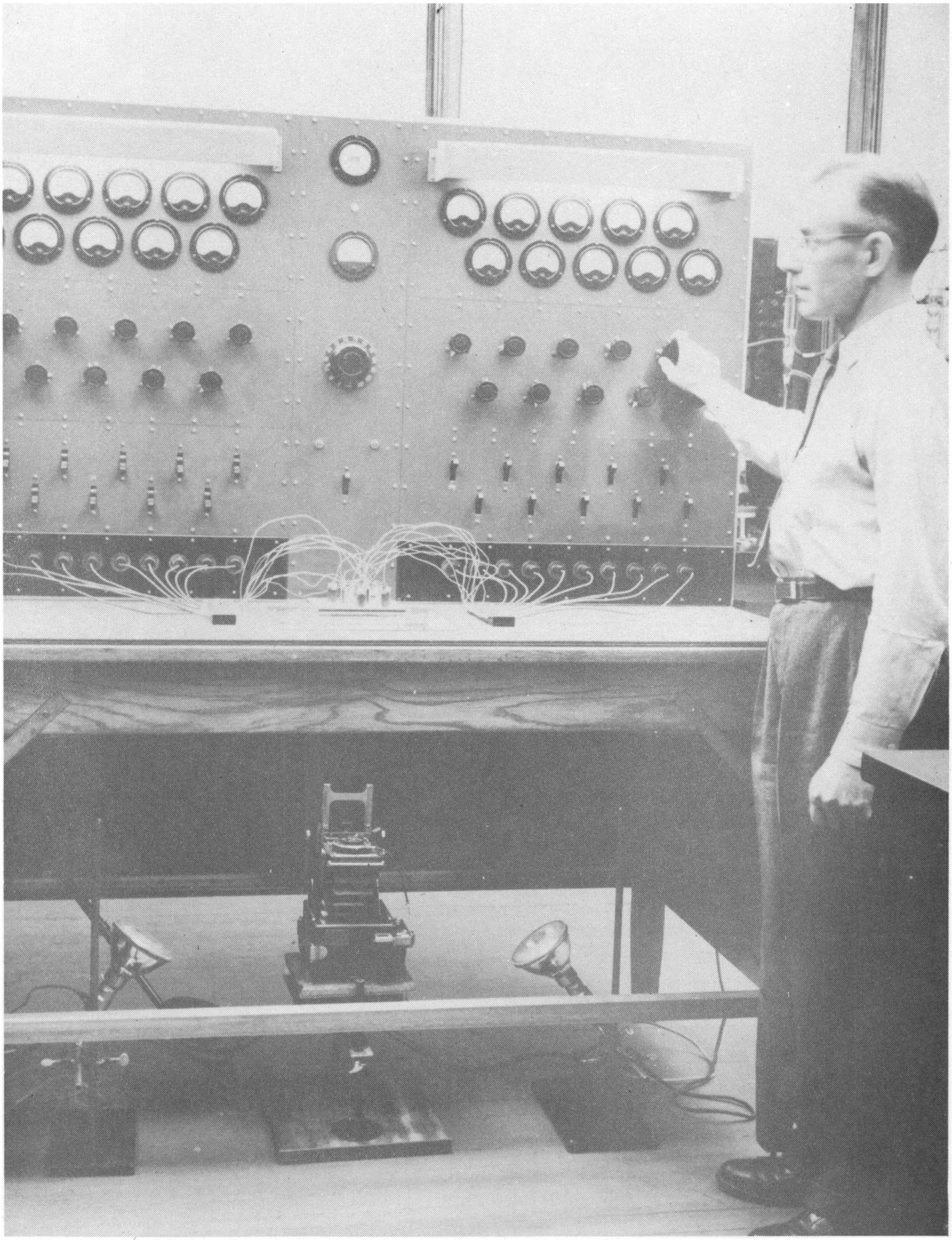

Figure 3. - Electrolytic model apparatus.

acre-foot. The oil at both ends of the shoestring has an API gravity of 32 degrees, but near the central part the gravity drops to 28 degrees. This low-gravity oil in the center of the shoestring may be a result of vertical faulting, of which direct evidence has been obtained by means of a diamond core.

THEORY OF ELECTROLYTIC MODEL

The statement of the analogy between the flow of liquids in rocks and the flow of electricity in sheet conductors was first published by C. S. Slichter in the 19th Annual Report of the U. S. Geological Survey, 1897-1898, p. 303. In this report he wrote: "I find the problem (of the movements of water in soils and rocks) is capable of mathematical treatment, and I show that the question is analogous to a problem in the conduction of heat or electricity or to any other problem involving the transfer of energy."

The theory of the electrolytic model as applied to oil-field problems has been presented by Muskat and Wyckoff,5/ Wyckoff and Botset, 6/ Swearingen,7/ Hurst and McCarty,8/ and Botset.9/ Horner and Bruce10/ have recently presented the analogy between the flow of electricity in a homogeneous conductor and the flow of a fluid in a homogeneous porous medium. In brief, the principle of operation of the model used in this investigation is the transference of positive copper ammonium ions in a copper ammonium chloride solution from the positive terminal of direct current to the negative terminal through a gelatin field containing zinc ammonium chloride ions. As the blue copper ammonium ions move under the influence of the potential applied through the field, they displace the colorless zinc ammonium ions and form a continually expanding pattern about the positive injection well. As the current continues to flow, the ions follow the steamlines set up by the applied potential and form a pattern that conforms to the volume of the reservoir that would be flooded by injected water. A photographic record is made at various stages of the flood's progress.

EXPERIMENTAL PROCEDURE

The equipment (fig. 3) and procedure used for investigating the different well arrays used in this investigation were essentially identical to those

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5/ Muskat, M., and Wyckoff, R. D., A Theoretical Analysis of Water Flooding ing Networks: Trans. A.I.M.E., vol. 107, 1934, p. 62.

6/ Wyckoff, R. D., and Botset, H. G., An Experimental Study of the Motion of Particles in Systems of Complex Potential Distribution: Physics, vol. 5, 1934, p. 265.

7/ Swearingen, J. S., Predicting Wet Gas Recovery in Re-cycling Operations: Oil Weekly, vol. 96, No. 3, Dec. 25, 1939, p. 30.

8/ Hurst, W., and McCarty, G. M., The Application of Electrical Models to the Study of Re-cycling Operations in Gas-Distillate Fields: Drilling and Production Practice, 1941, p. 228.

9/ Botset, H. G., The Electrolytic Model and its Application to the Study of Recovery Problems: Pet. Tech., T.P. 1945, Nov. 1945.

10/ Horner, W. L., and Bruce, W. A., Electrical Model Studies of Secondary Recovery, ch. 14: Secondary Recovery in the United States, 2d ed., Am. Petrol. Inst., 1950, pp. 195-203.

described by Botset.[11] The position of the wells, either injection or production, across the width of the field was determined by the cross-sectional shape of the field (fig. 4). The trough representing the shoestring sand was formed in a sheet of plastic 12 inches long, 6 inches wide, and 1/4 inch thick by using a shaping tool. The field's dimensions were 3/32 inch deep at the center, 3 inches wide, and 8 inches long. To obtain the curve of the bottom of the shoestring, the total depth of 3/32 inch was considered to equal 15 units. The cross section was divided into eight portions of equal length, four on each side of the center line. At a point one-fourth the distance from the center to either edge of the field, the curve rose one-fifteenth of the total depth; at the second point, three-fifteenths of the total depth; at the third, seven-fifteenths of the total depth; and at the fourth, the curve rose the remaining eight-fifteenths of the total depth, and a shoulder 1/64 inch in depth was provided to insure a void space between the gelatin field and the bakelite cover plate.

The shape of the electrolytic model field used in these tests was designed to give a cross-sectional area comparable to an average cross section of the oil-producing sand of the Paola shoestring. It must be remembered that a smooth, level, upper surface is required of the gelatin field; therefore, all sand-thickness variations must be compensated in the bottom curve of the trough.

With the shape of the field thus determined, the cross section of the field was divided into two equal areas, as well as into three equal areas. The centroid of the two equally divided areas was determined to be 0.533 inch from the center line. Using the three equal areas, the centroid of the outer two was 0.79 inch from the center line; the centroid of the center area was in the exact center of the cross section. These distances represent 106.6 feet and 158 feet, respectively, as the model field was constructed to a horizontal scale of 1 inch equals 200 feet. Most of the investigations were made by using well patterns consisting of alternate rows of two and three wells in a line perpendicular to the axis of the shoestring. As the rate of injection through any well was proportional to the thickness of the reservoir at that point, the distances mentioned above were determined for expected maximum flooding efficiency.

After the bakelite cover plate was drilled and the wells and trough were filled with their appropriate gelatin solutions, the cover plate was securely attached by means of cellophane tape to the sheet of plastic that contained the electrolytic field. The wells were then placed in their respective positions in the cover plate; the copper electrodes were inserted, and a small amount of the appropriate electrolyte solution was poured into each well, as shown in figure 4. The current then was applied, and the flow through the various injection and producing wells was adjusted to previously computed values. It has been determined that the maximum permissible current flow through any well in the equipment is 25 milliamperes; a greater current will cause the formation of a gas bubble or will cause the gelatin to split in the well tip, breaking the electrical circuit.

The different well arrays and techniques investigated were suggested by the operators of the Paola shoestring. It is felt that these patterns and the included data show the effect of well spacing, in both width and

[11] See footnote 9.

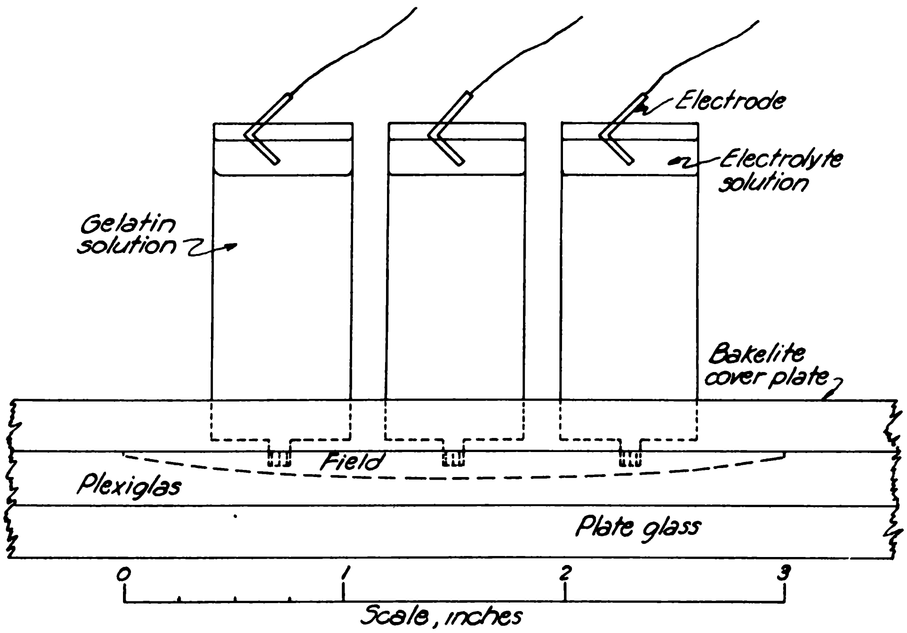

Figure 4. - End view of gelatin field used in electrolytic model study of a shoestring sand, showing machined plate of plexiglas, bakelite cover plate, plastic wells, and copper electrodes.

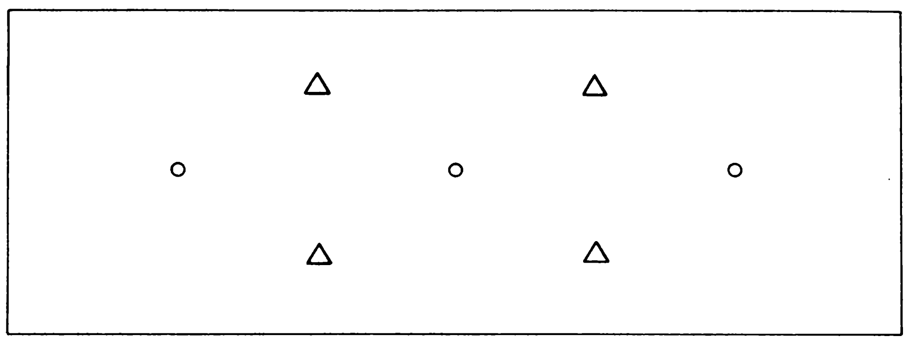

Figure 5. - Well array used in investigating pattern I.

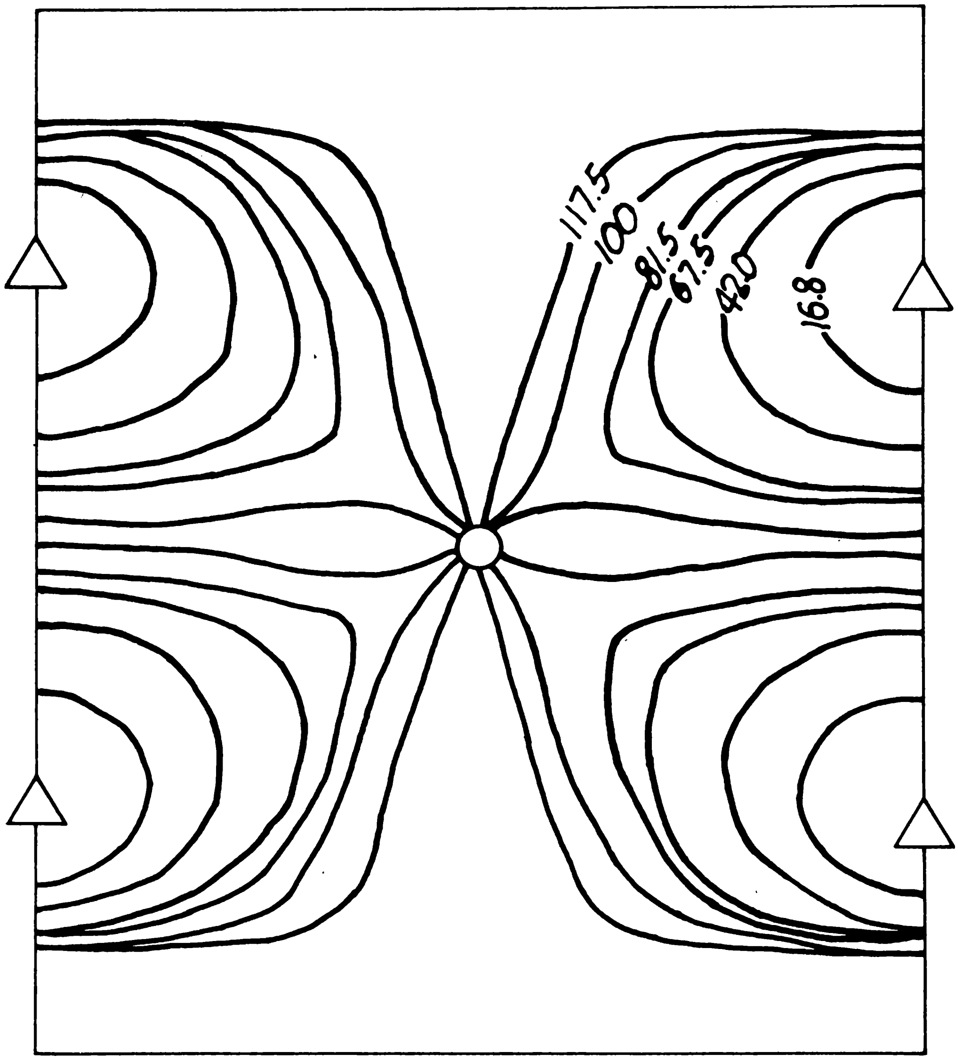

Figure 6. - Composite flood of pattern I - spacing 500 feet.

length of the shoestring, on water-flooding a shoestring sand. The distance along the axis of the reservoir between rows of injection wells in all of the tests represented either 500 or 600 feet; throughout this report this distance is referred to as spacing.

All these tests can be classified as follows:

1. Input rates proportional to the thickness of the gelatin at the well location.

2. Input rates proportional to the thickness of gelatin as given above, but with some producers converted to injection wells when the flood front reached them, or at other longer times.

3. Similar to 2 above, but also including delayed drilling to tap unflooded volumes in the central portion of a pattern.

Before describing each pattern, it should be made clear that all these floods are through a medium which represents uniform porosity and permeability, and the input and output fluids are of identical viscosities and identical densities. The variation of viscosity and density of the fluids involved in actual water-flooding operations usually does not introduce errors of great magnitude when compared to a study of this type.

DESCRIPTION OF TESTS

Figure 5 shows all the well positions used in flooding pattern 1. A small triangle is used to represent the position of an injection well. A small circle represents a producing well's position. Figure 6 shows positions of the flood front at various times during the test of pattern 1. In figure 6 and subsequent flood-front illustrations, only the area between two rows of injection wells is shown. It is known that the current flow lines are slightly distorted near the outer line of wells in an electrolytic model study of this type. Fancher analyzed this phenomenon in discussing some of the work of Kelton.[12] Therefore, to insure a true picture of the flood's progress, only the central portion of the flood, where the flow lines are analogous to field conditions, is included in this report. The flood-line designations denote percentage of "break-through" time. For the purpose of this paper, this time is defined as the time at which the flood front reaches a producing well. Breakthrough time in the producing well is shown as the 100-percent line.

Pattern 1 (fig. 6) consists of four injection wells and one central producer. The longitudinal scale distance between the rows of two injection wells is 500 feet, and the transverse distance between injection wells is 316 feet. As shown by these experiments, the outer edges of the shoestring,

12/ Kelton, F. C., An Electrolytic-Model Study of Cycling in the Grapeland Field, Houston County, Tex., sec. 9-A: Supplement to Secondary Recovery of Oil in the United States - 1942, Am. Petrol. Inst., 1943, pp. 199-205.

that is, the top and bottom of the illustration, would not be touched by the injected water, and as a result a bank of unrecoverable oil would be forced into this untapped area of the reservoir. The unflooded edge area shown in figure 6 represents 25 percent of the total unflooded volume in pattern 1 only; however, the unflooded edge volume is approximately equal in all of the flood patterns.

The volumetric efficiency obtained by this pattern at breakthrough was 60.0 percent. However, the test was continued to 117.5 percent of breakthrough time, and the final efficiency at this time was 69.7 percent. The volumetric efficiencies of all patterns or techniques were computed by first enlarging and then tracing the outline of the copper-zinc ion interface from the photographic record of the flood. The boundaries of the field (as shown in all illustrations of these floods) were then added to complete the tracing. The total area of each pattern was divided into rectangular units by dividing the width of the field into 30 equal parts. All unflooded areas in each rectangle were planimetered and, from the scale determined for each tracing, converted into unflooded acres. The unflooded volume under a particular rectangle is the product of the unflooded acres in that rectangle and its average thickness in feet. These unflooded volumes were totaled to give the final unflooded volume of the whole pattern. The total acre-feet in both the 500-foot or 600-foot spacing patterns were computed, and the volumetric efficiency of a flood pattern was obtained by subtracting the unflooded volume from the total volume, dividing this flooded volume by the total volume, and multiplying by 100.

Although pattern 1 (fig. 6) shows the lowest volumetric efficiency at break-through, the quantity of electricity, in milliampere-hours, needed to flood the pattern to break-through was also very low. The quantity (milliampere-hours) is the product of the total injection rate for all the injection wells in a pattern illustration and the time required to flood the pattern experimentally. For example, in the portion of the experimental field illustrated in figure 6, 10 milliamperes flowed through each of the four injection wells for a total of 40 milliamperes. Of the 40 milliamperes, only 20 flowed from the field through the producing well shown in the illustration; the remaining 20 milliamperes flowed through the two producing wells, which were not included in the composite flood illustration. The time required to obtain the flood front at 100 percent break-through time was 4.3 hours, or a total of 86.0 ma-hr. At 117.5 percent of break-through time, the pattern had used 101.0 ma-hr.

Pattern 2 (not illustrated) and pattern 3 (fig. 7) are identical, except that the distance between rows of injection wells in pattern 2 represented 500 feet, whereas the distance between rows of injection wells in pattern 3 represented 600 feet. The producing wells were spaced 106.6 feet from the axis of the shoestring, or 213.2 feet apart, whereas the two outer injection wells were 158 feet from the axis of the sand body. The thickness of the gelatin field at the position of the center well was 0.094 inch, whereas the thickness of the gelatin field at the position of an outer injection well was 0.074 inch. Therefore, the center injection well's current or injection rate was 1.28 times as large as an outer well's injection rate. This flood

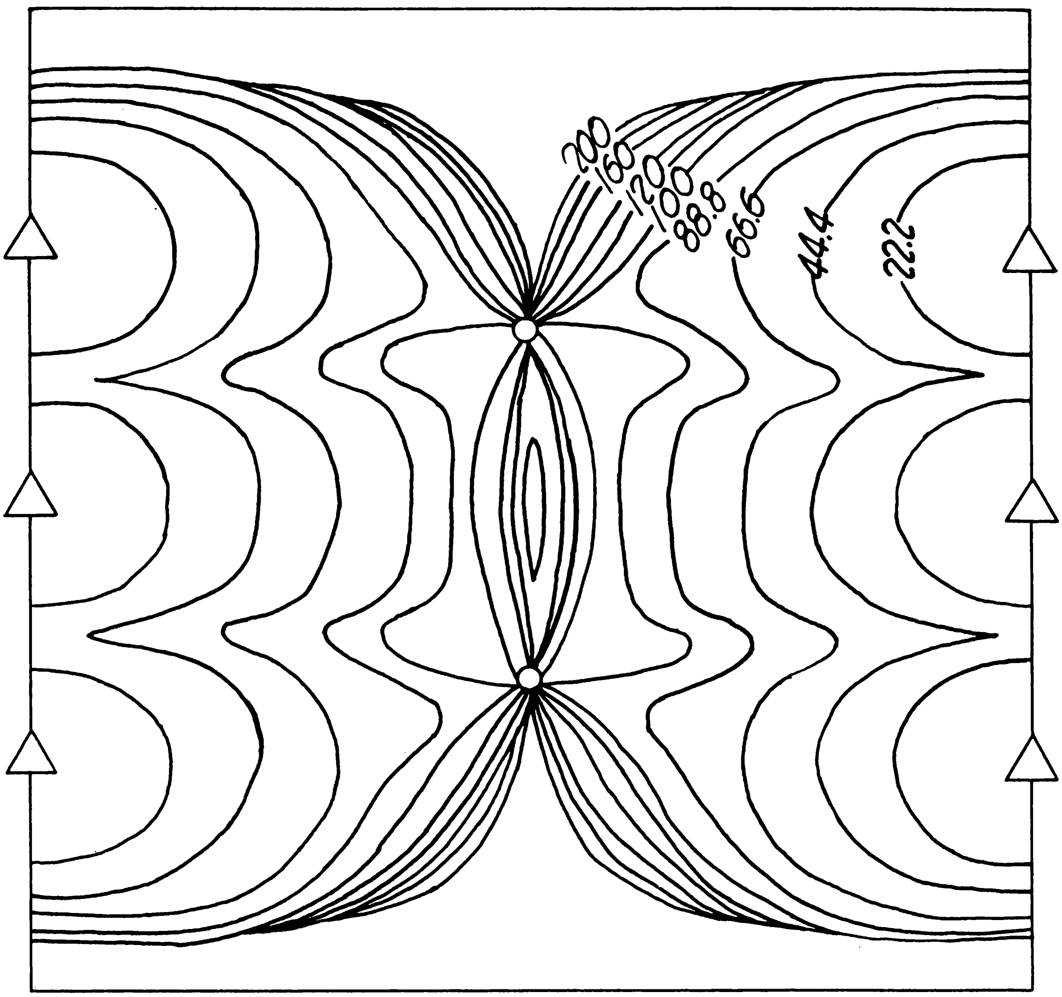

Figure 7. - Composite flood of pattern 3 - spacing 600 feet.

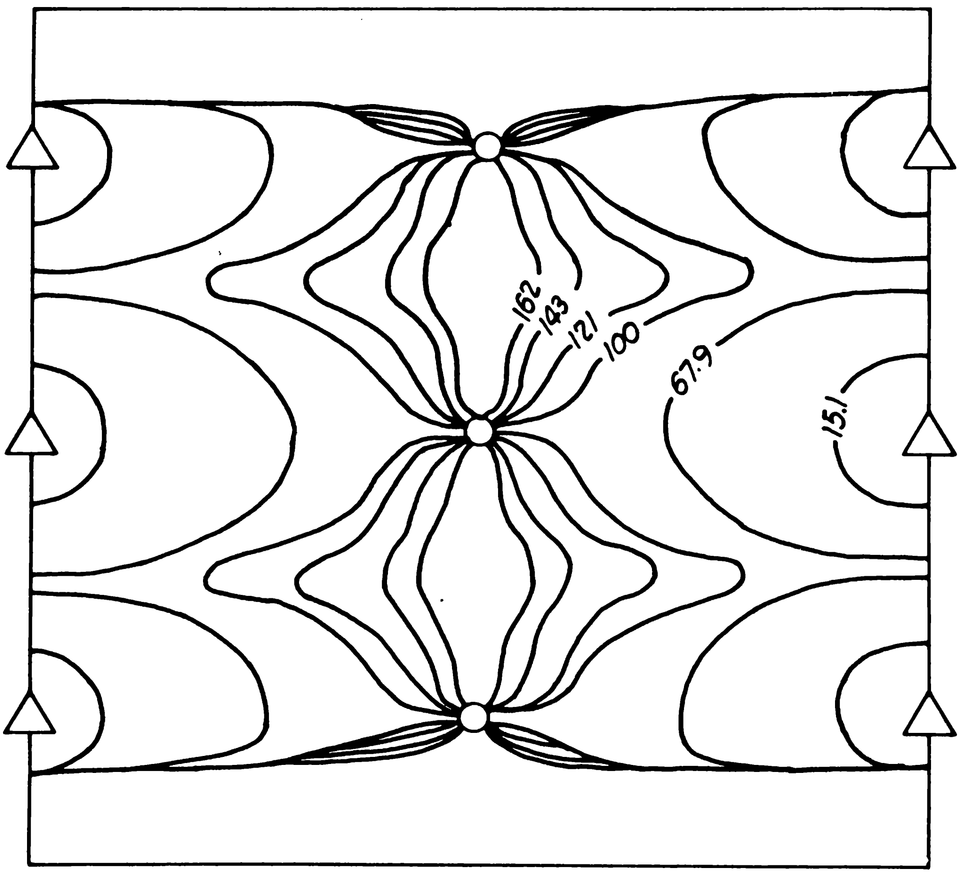

Figure 8. - Composite flood of pattern 4 - spacing 600 feet.

pattern and rate of injection produced a volumetric efficiency at break-through of 73.0 percent, with rows of injection wells scaled at 600 feet apart, and 70.8 percent when the distance between rows of injection wells represented 500 feet. The volumetric efficiencies at other percentages of break-through time are shown in table 1.

TABLE 1. - Comparison of patterns 2 and 3

Status of flood front, percent of break-through time	Volumetric efficiency, percent. Represented distance between rows of injection wells	
	500 feet	600 feet
100............	70.8	73.0
125............	-	82.9
150............	83.8	87.3
175............	-	91.7
198............	-	92.9
200............	90.3	-
250............	91.5	93.9
300............	93.3	-
350............	93.7	-

The 500-foot spacing of this flood used an amount of electricity equal to 76.3 ma-hr. at break-through, whereas the 600-foot pattern used 98.1 ma-hr., or a 3.1 percent increase in volumetric efficiency with a 28.6 percent increase in the total ma-hr. used.

A line-drive flood, pattern 4, is shown in figure 8. The position of the outer line of wells, either production or injection, parallel to the axis of the field, was moved out toward the edges of the gelatin field to ascertain what effect a wider well spacing across the width of the shoestring would have on the unfloodable edges. The distance between these well positions and the axis of the field was 1.04 inches. This scaled distance would be 208 feet from the axis of the field, or 92 feet from the edge of the producing horizon. The spacing between rows of injection wells was scaled at 600 feet. This flood pattern contains six injection wells and three producing wells. Break-through occurred in all producing wells at the same time. At break-through, the volumetric efficiency of this line drive was 61.7 percent; at 121 percent of break-through, 69.8 percent; at 143 percent of break-through, 73.3 percent; and at 162 percent of break-through, 81.1 percent. The total amount of electricity used was 154.8 ma-hr. No apparent increase in volumetric efficiency was obtained, nor were more of the edges of the gelatin field flooded by increasing the well spacing across the width of the shoestring.

The remaining patterns investigated were changed after break-through had taken place; this change is thought of as changing the stage. A stage is a pattern arrangement until break-through has taken place. The position of the flood front during these different stages and the changes from producing to injection wells are shown in different lines; that is, the first stage as a solid line; second stage, dotted line; third stage, long-and-short dashed line.

Pattern 5 (fig. 9) shows the first flood pattern employing more than one stage of flooding. This pattern contained four injection wells and two producers in the first stage. The flood front in this first stage is shown as a solid line. The second stage was initiated when the two producing wells on the axis of the shoestring experienced break-through. These two wells then were converted to injection wells, and a single central producer was drilled midway between the rows and on the axis to drain the central portion of the pattern. This is the first flood pattern using a delayed drilling procedure.

The second-stage flood pattern thus contained six injection wells and one producing well, and the distance between rows of injection wells was 500 feet. An injection well and a producer in the first stage were spaced 158 feet apart. The second stage of the flood was continued until 164 percent of break-through; at this time the flood attained a volumetric efficiency of 82.6 percent, using an amount of electricity equal to 102.2 ma-hr.

In pattern 6 (fig. 10), the first stage has been reversed slightly from the previous well pattern (fig. 9), in that two injection wells in the pattern were used with five producing wells. When the four outer producing wells experienced break-through, they were converted to injection wells, and the flood continued. The distance between injection wells across the shoestring in the second stage is 158 feet, and 500 feet separate rows of injection wells. This flood was continued until 237 percent of break-through time and attained a volumetric efficiency of 76.6 percent, using 122.7 ma-hr.

Pattern 7 (fig. 11) shows a flood pattern using four injection wells and two producing wells in the first stage. Along the axis of the shoestring in the first stage, the distance between rows of injection wells was 600 feet; the distance between injection wells was 213.2 feet; and the two production wells in the first stage were spaced 316 feet apart. The first stage of this pattern was continued until 200 percent of break-through time. At this time the producing wells were converted, as shown, to input status, and a central producer was drilled to drain the central portion of the pattern, making a pattern of six injection wells and one producing well. After converting to the second stage, the injection was continued until 2600 percent of break-through time in this stage; break-through time was 6 minutes in this stage, as compared with 2.2 hours in the first stage of this pattern. In the first stage of the test shown in figure 11, the pattern showed a volumetric efficiency of 64.0 percent at 100 percent of break-through, 82.0 percent at 150 percent of break-through, and 87.3 percent at 200 percent of break-through. At the close of the second stage, the volumetric efficiency of this flood was 95.8 percent, using 234.8 ma-hr.

The pattern and technique of pattern 8, shown in figure 12, are virtually the same as the preceding investigation, the only exceptions being that the spacing was 500 feet and the first stage was continued only until break-through time. The pattern was then converted, and injection continued to 186 percent of break-through time in the second stage. At this time 89.5 percent of the total volume was flooded, using 122.9 ma-hr.

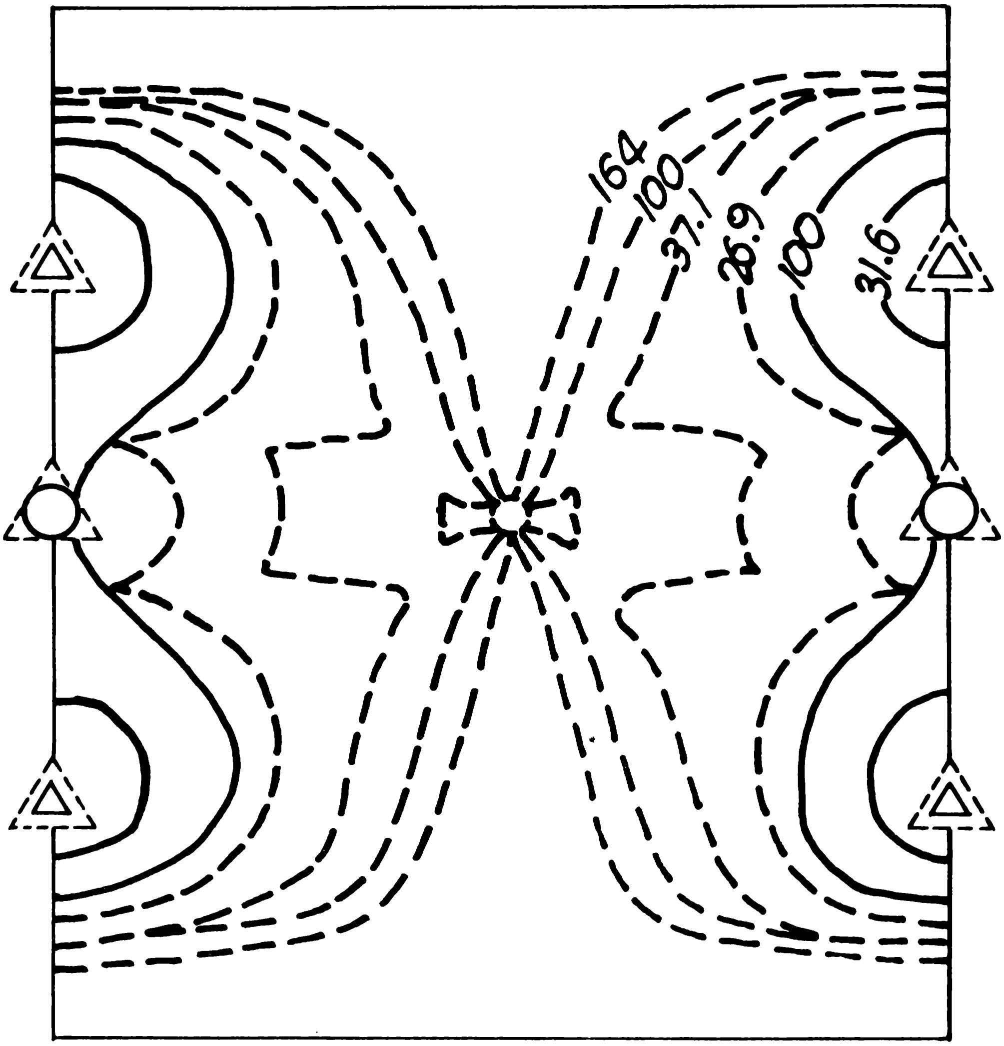

Figure 9. - Composite flood of pattern 5 - spacing 500 feet.

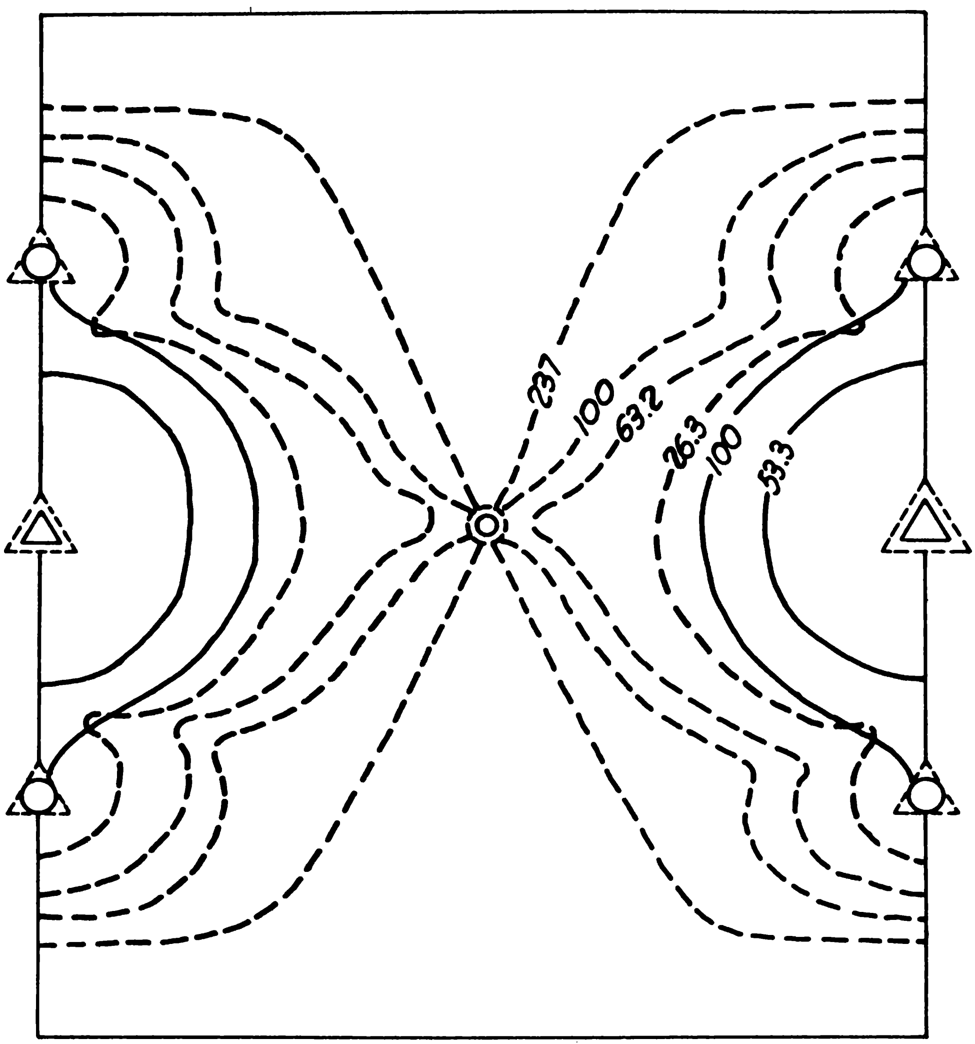

Figure 10. - Composite flood of pattern 6 - spacing 500 feet.

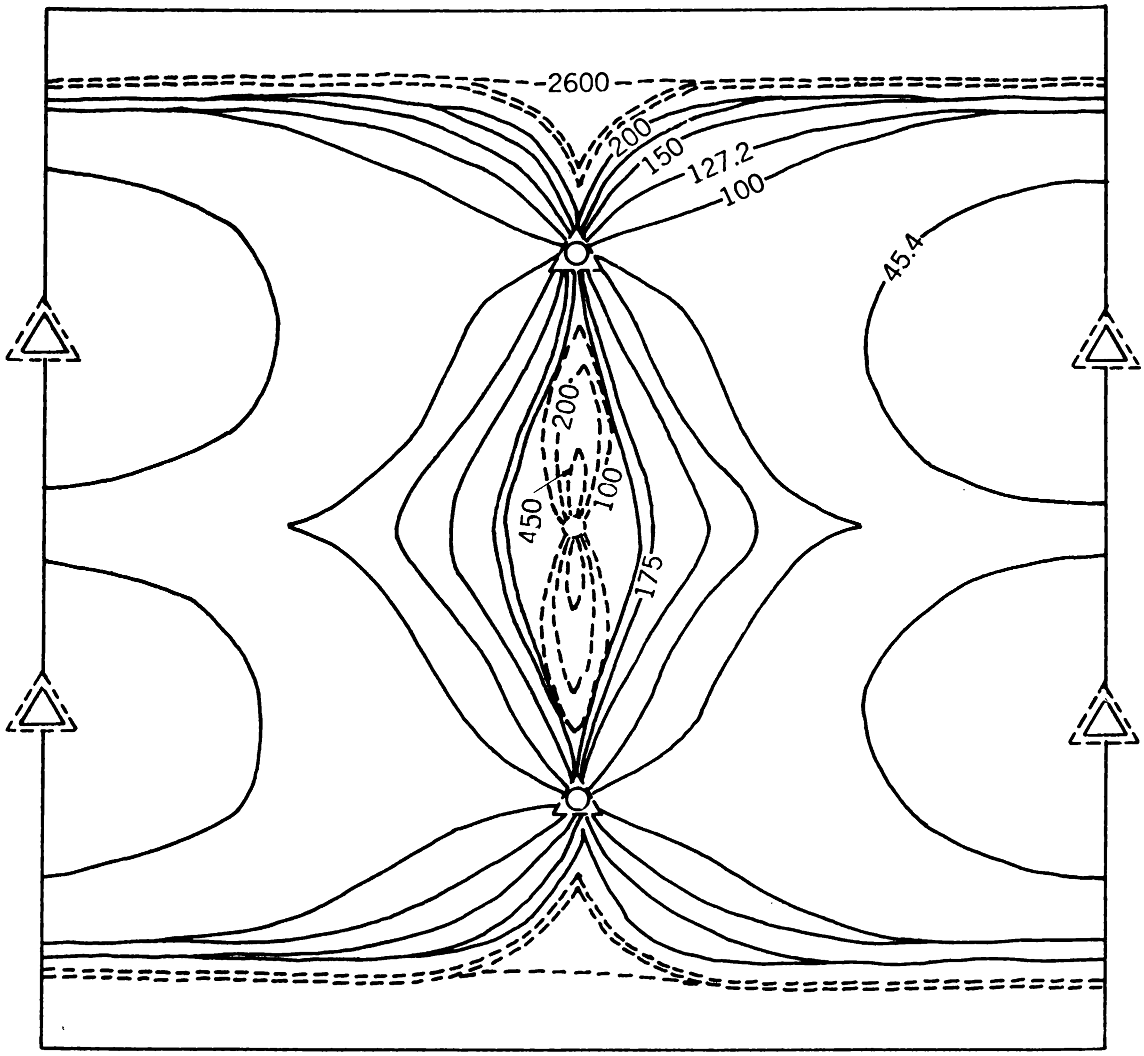

Figure 11. - Composite flood of pattern 7 - spacing 600 feet.

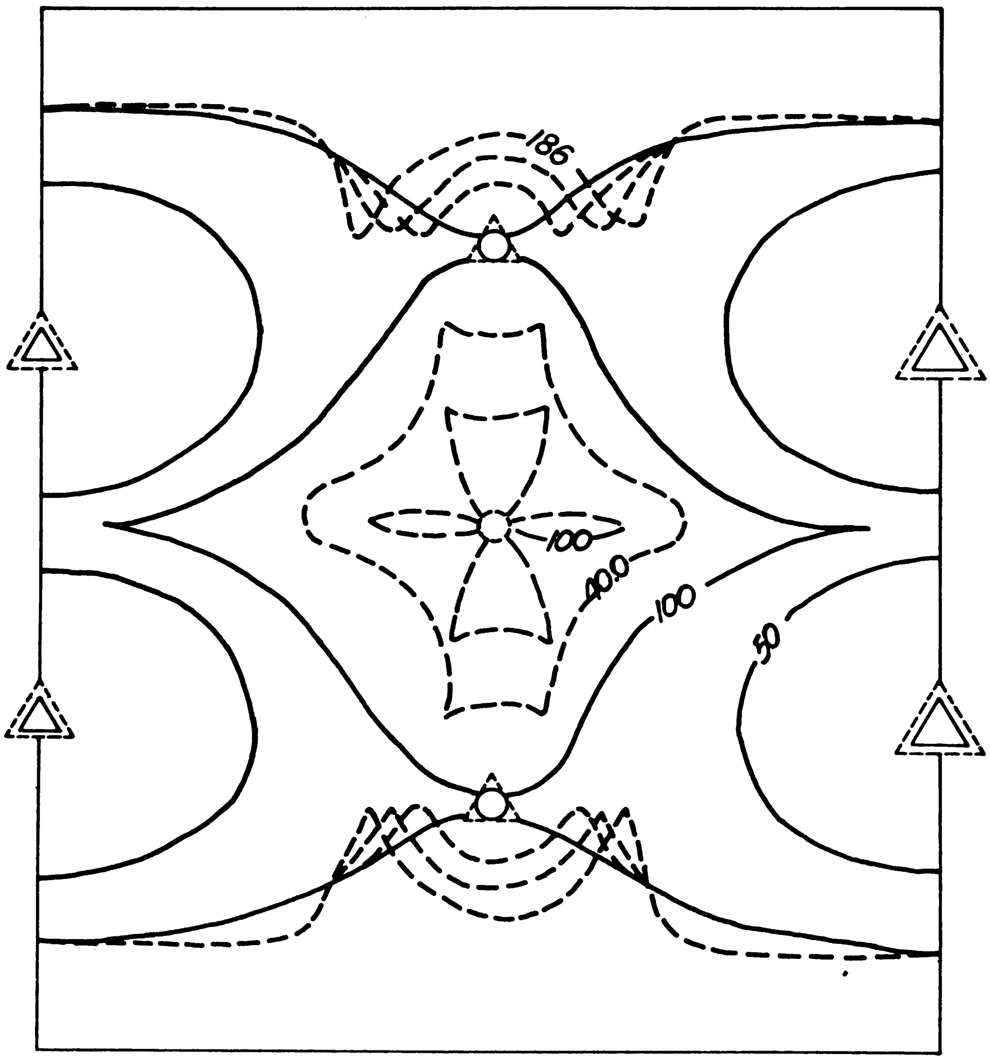

Figure 12. - Composite flood of pattern 8 - spacing 500 feet.

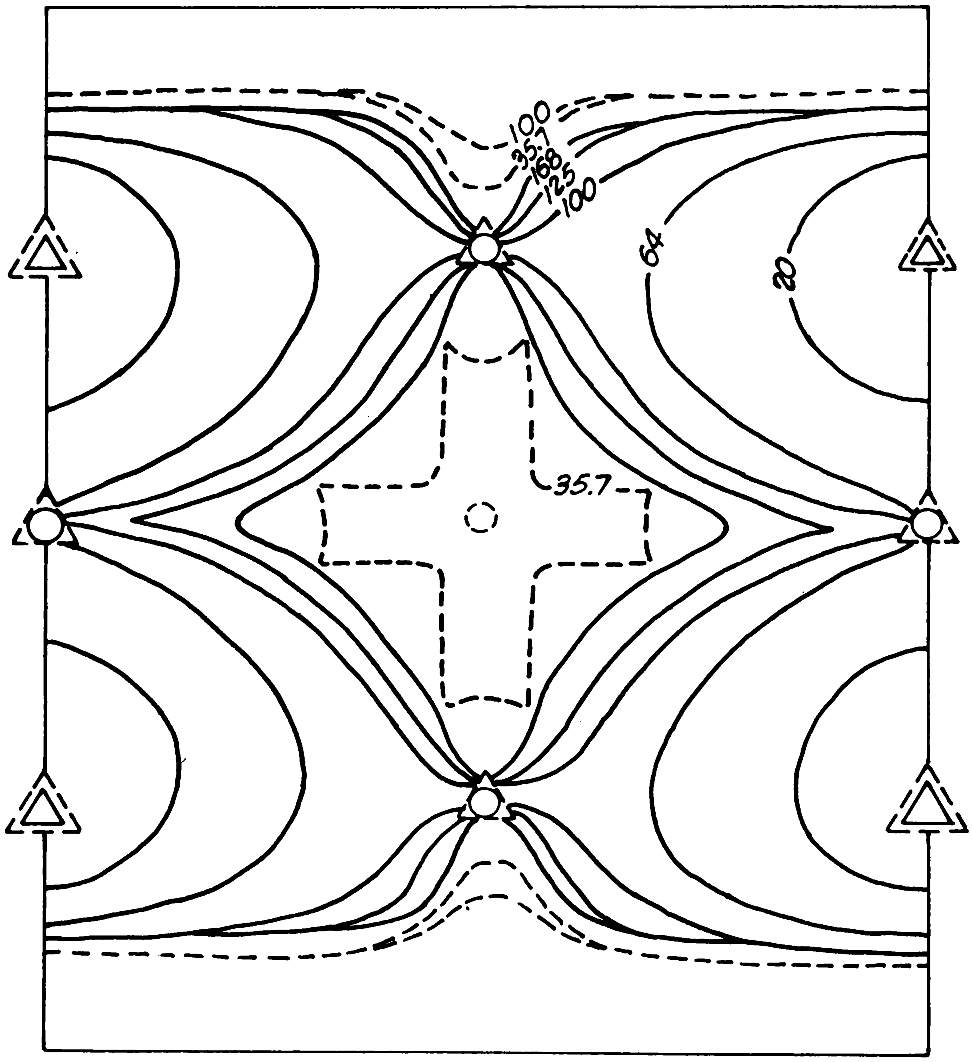

Figure 13. - Composite flood of pattern 9 - spacing 500 feet.

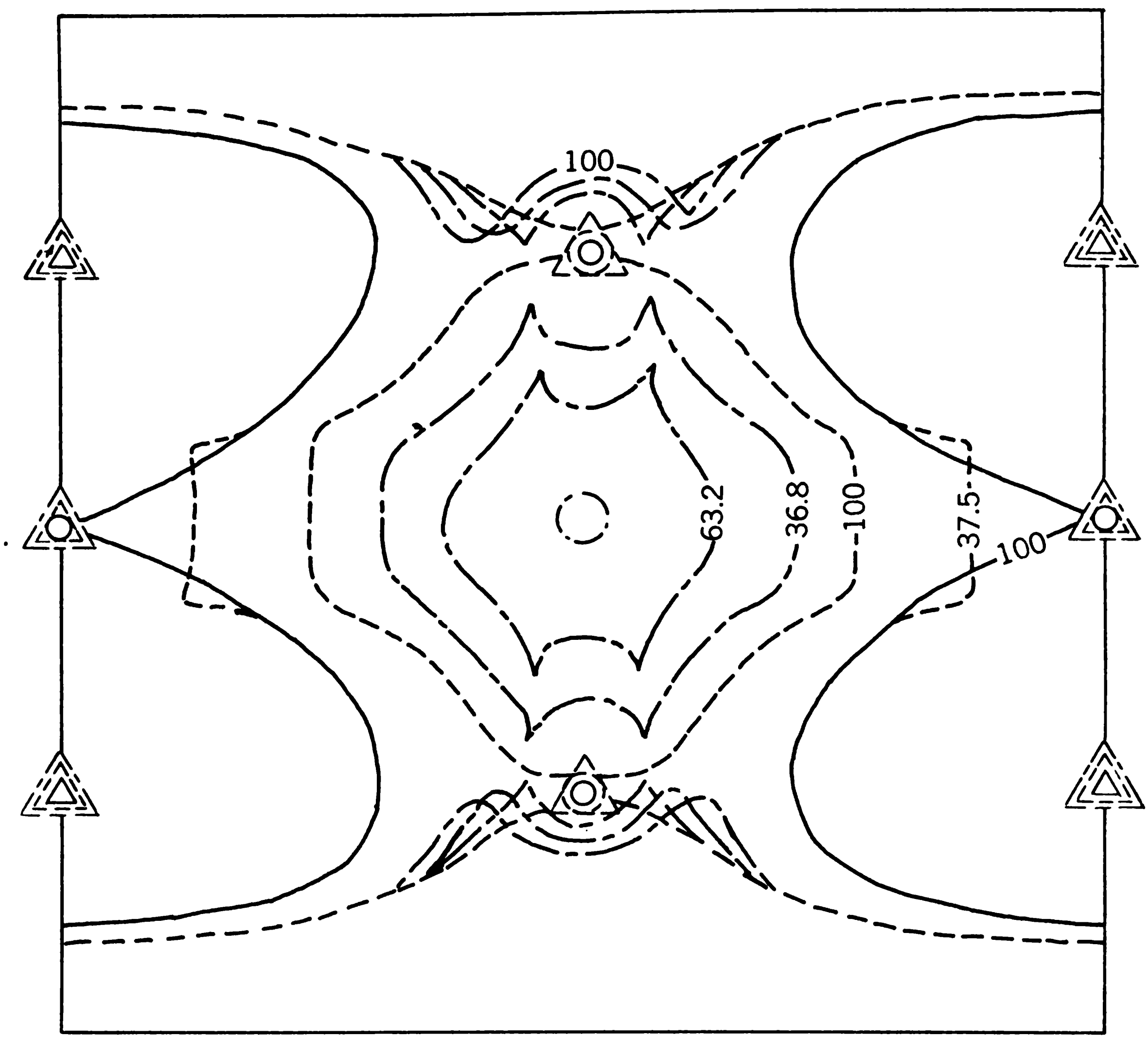

Figure 14. - Composite flood of pattern 10 - spacing 600 feet.

Four injection and four producing wells were used in the first stage of pattern 9; the composite flood is shown in figure 13. The second stage of the pattern contained eight injection and one producing well. All the well positions along the outer edges of the shoestring are located 158 feet from the axis of the field, whereas 500 feet along the axis of the field separates the injection wells in the first stage. Break-through in the first stage for the pattern was considered to be the time of arrival of the ion interface at those producing wells that were 250 feet from the injection wells. This pattern was flooded until 168 percent of break-through time before the second stage of the flood was started. The second stage of the pattern was initiated by changing four producing wells to injection wells and drilling a central producer. This stage of the flood was continued until the copper ions had replaced the zinc ions in the central portion of the field. The position of the flood front along the edge of the sand body at this time is shown as the 100 percent break-through-time line in the second stage of figure 13. When the central portion of the shoestring was completely colored by the injected ions, pattern 9 had flooded 86.9 percent of the total volume. During the first stage of this pattern, 60.6 percent of the total volume was flooded at 100 percent of break-through time; 69.8 percent of the volume was flooded at 125 percent of break-through time; and at 168 percent of break-through, 76.7 percent of the total volume was flooded. The quantity of electricity used in both stages of the test was 193.2 ma-hr.

The flooding technique used in pattern 10 (fig. 14) has three stages. This technique has many detrimental economic factors in its completion but was investigated to examine the possibility of increasing the flooded volume of the field by using more than two stages. The first and second stages of this flood are shown as in the preceding composite flood illustrations; the third stage of this flood is shown as a long-and-short dash line. The distance between rows of injection wells in the third stage was 600 feet; 158 feet separated the wells on the outer edges of the shoestring from the axis of the field. Four injection and four producing wells were used in the first stage; six injection and two producing wells were used in the second stage; eight injection and one producer, which was added at conversion time, were used in the third and final stage of this flood pattern.

Break-through in the first stage was considered to have taken place when the ion flood front reached those producers that were positioned on the axis of the field, even though the injected ions had not reached those producers that were 300 feet from the injection wells. The two producing wells that experienced break-through then were converted to injection wells, and the flood continued until it broke into the producers parallel to the axis of the field. At this stage in the flood the producer shown in the center of the illustration was inserted in the cover plate, and all other wells shown were converted to injection wells. This flooding pattern and technique show a volumetric efficiency of 87.9 percent at the time when the center of the pattern was completely flooded. The flood front at this time is shown as the 100 percent break-through-time line of the third stage. This flood required 144.8 ma-hr. to attain the above volumetric efficiency.

DISCUSSION OF RESULTS

The results obtained by Wyckoff and Botset[13] from the use of the electrolytic model on simple floods have been proved to have an accuracy of 95 to 98 percent when compared with results obtained by mathematical analysis for simple floods. Therefore, the results of this study are assumed to be within that limit of accuracy. Patterns 2 and 3 were investigated for reproducibility. At break-through time, pattern 2 showed volumetric efficiencies of 69.8 percent and 70.8 percent, whereas pattern 3 showed 71.7 percent and 73.0 percent volumetric efficiency, or an average variation of 1.6 percent. These results show that any pattern or technique may be reproduced with good accuracy, and it is logical to assume the results obtained from this study are within the accuracy of the electrolytic model.

The amount of oil that could be produced by water-flooding a reservoir that has the characteristics of the Paola shoestring can be determined from the volumetric efficiencies and pertinent core-analysis data. However, it has been mentioned previously in this report that the thin edges of a shoestring reservoir will not be swept by a water flood, although this unflooded volume contains an appreciable quantity of oil. The pressure distribution established by the water flood would force a portion of the theoretically recoverable oil from the flooded portion of the reservoir into these edges. The oil saturation of the unflooded volume would be increased, and the void spaces in this portion of the reservoir would be completely filled. The operators of the Paola shoestring have found this phenomenon to occur in the field. One old, abandoned, but improperly plugged primary production well in the thin edge area of the shoestring flowed oil to the surface of the ground after water had been injected into the sand; the oil forced into these edges must have moved into this area from the portion of the sand that had been swept by the water flood.

The gas-filled portion of the Paola shoestring amounted to 16 percent of the total porosity before the water-flooding operation started, and the authors have assumed this 16-percent void space to be resaturated with oil, and the liquid saturation of the unflooded portion of the shoestring to be increased to 100 percent during the water-flooding operation. If the liquid saturation of the unflooded volume of sand is not increased to 100 percent, more oil will be recovered than is computed in this report. It is further assumed that the residual oil saturation at the end of the flood will be 25 percent in the flooded portion of the field; consequently, the oil recovered amounted to 24 percent of the pore space in that portion of the field. An equation for determining recoverable oil has been derived from these assumptions and pertinent core data; a summary of saturation conditions is listed below.

	Fraction of porosity
Oil saturation at start of flood...............	0.49
Water saturation at start of flood.............	.35
Gas saturation at start of flood...............	.16
Oil saturation of flooded portion of reservoir at end of flood..............................	.25
Oil removed from flooded portion of reservoir..	.24

13/ See footnote 6.

Recoverable oil was determined by the equation:

$$R = \frac{0.24P(V_s) - 0.16P\ (V_u)}{0.49P} \times 100,$$

or,

$$R = \frac{0.24V_s - 0.16V_u}{0.49} \times 100;$$

where,

R = recoverable oil in percent of total oil in portion of reservoir studied,

V_s = fraction of total reservoir swept by flood (volumetric efficiency)

V_u = fraction of total reservoir not swept by flood $(1 - V_s)$,

P = total pore space in reservoir, barrels.

From this equation, the percentage of oil recoverable was determined for each of the floods investigated. The average area of the four cross sections shown in figure 2 was 14,023 sq. ft., and the gross volume of a 500-foot pattern was 161.0 acre-feet.

$$\frac{(14{,}023 \text{ sq. ft.})\ (500 \text{ ft.})}{(43{,}560 \text{ sq. ft. per acre})} = 161.0 \text{ acre-feet}$$

A 600-foot spacing contained 193.2 acre-feet of oil-bearing sandstone. The total volume of oil in 161.0 acre-feet is equal to:

$$(7{,}758\ \frac{\text{bbl.}}{\text{ac.-ft.}} \times (161 \text{ ac.-ft.}) \times (0.217 \text{ porosity})$$
$$(0.49 \text{ oil saturation}) = 132{,}805 \text{ bbl.}$$

The 193.2 acre-feet within a 600-foot spacing contained 159,373 barrels of oil. The volume of oil produced at specific times for the various patterns is shown in table 2 as theoretical oil recovery from the pattern in barrels. This oil recovery is also expressed on an acre and acre-foot basis in the table.

The quantity, theoretical water injected, was computed by first establishing a volume of water injected - milliampere-hour relationship for each of the patterns. This relationship was determined by computing the volumetric efficiency at various times before the ion interface from any individual injection well reached the ion interface from any other injection well and, also, at break-through time.

A 500-foot spacing in the Paola shoestring contained 161.0 acre-feet of "pay", which is equal to 7,011,500 cubic feet of sandstone; a 600-foot spacing would contain 8,413,800 cubic feet of sandstone. The following calculation was made to determine the total barrels of pore volume available to the injected water in the 500-foot spacing pattern, based on the assumption that 40 percent of the total pore volume would be filled with injected water; the 24 percent of the pore volume from which oil was recovered and the 16 percent of the pore volume that initially contained gas:

$$\frac{\left(\begin{array}{c}7{,}011{,}500 \text{ cubic feet}\\ \text{of sandstone}\end{array}\right) \times (0.217 \text{ porosity}) \times \left(\begin{array}{c}0.40 \text{ pore volume}\\ \text{available to water}\end{array}\right)}{(5.61 \text{ cubic feet/barrel})}$$

$=$ 108,484 bbl. of pore volume available to the injected water, or the effective pore volume.

A comparable calculation for the 600-foot spacing shows 130,181 barrels of effective pore volume.

Knowing the pore volume into which the injected water could flood and the volumetric efficiency, the volume of water that had to be injected into the pattern was determined. This volume of water was divided by the total milliampere-hours the pattern required to that time. From one to four of these calculations were made for each pattern and averaged to give the relationship for each pattern. For example, in pattern 3, which was investigated using a 600-foot spacing, two photographs that could be used for this calculation were made of the flood before break-through occurred. The first photograph was made after 12 minutes had elapsed; the second photograph after 24 minutes had elapsed. Break-through time occurred in 135 minutes (2.25 hours), as shown in table 2. Pattern 3 had a volumetric efficiency of 6.52 percent at the time the first picture was made and 12.59 percent when the second picture was made. The volume of water that had to be injected to attain the 6.52 percent volumetric efficiency was determined as follows:

$$\left(\begin{array}{c}130{,}181 \text{ bbl. of}\\ \text{effective pore volume}\end{array}\right) \times (0.0652) = 8{,}479 \text{ bbl. of water}$$

This volume of water was divided by the total milliampere-hours used to the time the picture was made. The current was 43.6 milliamperes and the time was 0.2 hour, therefore:

$$\frac{8{,}479 \text{ bbl. of water}}{(43.6 \times 0.2) \text{ ma-hr.}} = 972.3 \text{ bbl. of water injected per ma-hr.}$$

TABLE 2. - Summary of electrolytic model studies as applied to water flooding a shoestring sand

Pattern or technique No.		Pattern length, spacing, ft.	Pattern area, acres	Pattern volume, acre-feet	Length of test, hrs.	Quantity of electricity, ma-hrs.	Volumetric efficiency, percent	Status of flood, percent of break-through time	Theoretical oil recovery, percent of oil in place	Theoretical oil recovery from pattern, bbl.	Theoretical oil recovery from pattern, bbl. per acre	Theoretical oil recovery from pattern, bbl./acre-ft.	Theoretical water injected into pattern, bbl.	Theoretical water injected, percent of effective pore volume	Development cost per pattern, dollars	Water cost per pattern, dollars	Development and water cost per bbl. of produced oil, dollars	Well density, acres per well	Development cost per acre, dollars
1		500	6.89	161.0	4.30	86.0	60.0	100.0	16.3	21,647	3,142	135	63,029	58.1		958	0.321		
					5.05	101.0	69.7	117.5	24.2	32,139	4,665	200	74,023	68.2	6,000	1,125	.222	2.30	871
2		500	6.89	161.0	1.75	76.3	70.8	100	25.1	33,334	4,838	207	79,489	73.3		1,208	.336		
					2.63	114.7	83.8	150	36.0	47,810	6,939	297	119,494	110.1		1,816	.247		
					3.50	152.6	90.3	200	41.1	54,583	7,922	339	158,978	146.5		2,416	.227		
					4.38	191.0	91.5	250	42.0	55,778	8,096	346	198,984	183.4		3,025	.233		
					5.25	228.9	93.3	300	43.5	57,770	8,385	359	238,468	219.8		3,625	.236		
					6.13	267.3	93.7	350	43.8	58,169	8,443	361	278,473	256.7	10,000	4,233	.245	1.38	1,451
3		600	8.26	193.2	2.25	98.1	73.0	100	26.9	42,871	5,190	222	94,304	72.4		1,433	.266		
					2.81	122.5	82.9	125	35.0	55,781	6,753	289	117,759	90.5		1,790	.211		
					3.38	147.4	87.3	150	38.6	61,518	7,448	318	141,696	108.8		2,154	.198		
					3.94	171.8	91.7	175	42.2	67,255	8,142	348	165,151	126.9		2,510	.186		
					4.45	194.0	92.9	198	43.1	68,690	8.316	356	186,492	143.3		2,835	.187		
					5.62	245.0	93.9	250	44.0	70,124	8,490	363	235,519	180.9	10,000	3,580	.194	1.65	1,211
4		600	8.26	193.2	2.65	95.4	61.7	100	17.7	28,209	3,415	146	74,011	56.9		1,125	.465		
					3.20	115.2	69.8	121	24.4	38,887	4,708	201	89,372	68.7		1,358	.344		
					3.78	136.1	73.3	143	27.2	43,349	5,248	224	105,586	81.1		1,605	.314		
					4.30	154.8	81.1	162	33.5	53,390	6,464	276	120,094	92.3	12,000	1,825	.259	1.38	1,453
5	**First stage**	500	6.89	161.0	1.90	23.9		100					22,669	20.9		345			
	Second stage				3.80	78.3							74,268	68.5		1,129			
	Total				5.70	102.2	82.6	164	34.8	46,216	6,708	287	96,937	89.4	8,115	1,473	.208	1.72	1,178
6	**First stage**	500	6.89	161.0	1.50	30.0		100					29,697	27.2		451			
	Second stage				4.50	92.7							91,764	84.6		1,395			
	Total				6.00	122.7	76.6	237	29.9	39,709	5,763	247	121,461	112.0	10,230	1,846	.304	1.72	1,485
7	**First stage**	600	8.26	193.2	2.20	88.0	64.0	100	19.6	31,237	3,782	162	79,790	61.3		1,213	.366		
					2.80	112.0	74.4	127.2	28.0	44,624	5,402	231	101,550	78.0		1,544	.264		
					3.30	132.0	82.0	150	34.3	54,665	6,618	283	119,684	91.9		1,819	.220		
					3.85	154.0	86.3	175	37.8	60,243	7,293	312	139,632	107.3		2,122	.205		
					4.40	176.0	87.3	200	38.6	61,518	7,448	318	159,579	122.6		2,426	.205		
	Second stage				0.10	2.3	92.6	100	42.9	68,371	8,277	354	161,665	124.2		2,457	.186		
					0.20	4.5	93.6	200	43.7	69,646	8,432	361	163,659	125.7		2,488	.183		
					0.30	6.8	93.9	300	44.0	70,124	8,490	363	165,745	127.3		2,519	.182		
					0.45	10.2	94.5	450	44.5	70,921	8,586	367	168,828	129.7		2,566	.180		
					0.60	13.6	95.2	600	45.1	71,877	8,702	372	171,910	132.1		2,613	.178		
					1.00	22.6	95.4	1,000	45.2	72,037	8,721	373	180,071	138.3		2,737	.180		
					2.60	58.8	95.8	2,600	45.6	72,674	8,798	376	212,893	163.5		3,236	.186		
	Total				7.00	234.8	95.8		45.6	72,674	8,798	376	212,893	163.5	10,230	3,236	.186	1.65	1,238
8	**First stage**	500	6.89	161.0	2.00	80.0		100					62,704	57.8		953			
	Second stage				1.90	42.9							33,625			511			
	Total				3.90	122.9	89.5	186	40.4	53,653	7,787	333	96,329	88.8	10,230	1,464	.218	1.38	1,485
9	**First stage**	500	6.89	161.0	2.50	97.5	60.6	100	16.8	22,311	3,238	139	72,248	66.6		1,098	.607		
					3.10	120.9	69.8	125	24.3	32,222	4,677	200	89,587	82.6		1,362	.428		
					4.20	163.8	76.7	168	29.9	39,709	5,763	247	121,376	111.9		1,845	.360		
	Second stage				1.40	29.4							21,785			331			
	Total				5.60	193.2	86.9		38.3	50,864	7,382	316	143,161	132.0	12,460	2,176	.288	1.01	1,808
10	**First stage**	600	8.26	193.2	1.00	39.0		100					29,550	22.7		449			
	Second stage				1.70	68.0		100					51,524	62.3		783			
	Third stage				1.80	37.8							28,641			435			
	Total				4.50	144.8	87.9		39.1	62,314	7,544	323	109,715	84.3	12,460	1,668	.227	1.38	1,508

Comparable calculations were made for the other two pictures (one at 24 minutes and the other at break-through time). The average of these three values equaled 961.3 bbl. of water injected per ma-hr. No explanation can be given for the variation between these individual calculations for any one pattern. The quantity, barrels of water per ma-hr., varied slightly between patterns, probably because the minute variations in the volume of water that evaporated while boiling the gelatin field solution for each investigation is reflected in the above relationship, although very little error is induced because the unit volume of gelatin flooded by the unit quantity of electricity in any pattern is a function of the thickness of the gelatin field.

The theoretical volumes of water injected into each pattern at specific times and volumetric efficiencies is shown in table 2. From the total volume of the pattern available to the injected water, the cumulative input, in percent of effective pore volume, was calculated.

The various well arrays have been studied to determine which well pattern or flooding technique would be most profitable to the field operator. In any economic study of water-flooding projects, consideration must be given to the development costs and operating expenses. As all producing wells in the Paola shoestring are equipped to flow, the estimated cost of an injection or a producing well in this area is approximately $2,000. It is estimated that $115 would be needed to convert a flowing producer to an injection well. The development costs per pattern reported in table 2 include only well-completion and well-conversion costs.

Injection water costs also were considered and calculated by Yuster's[14/] equation for determining the delivered cost of water to an injection well per barrel - in which D, the cost in dollars per barrel injected, is equal to 0.012 + 0.00000445 P; where P is the wellhead injection pressure. Using an injection pressure of 720 p.s.i., the cost per barrel of water injected in any of the patterns studied is equal to $0.0152, and water cost per pattern is shown in table 2.

The pre-eminence of any pattern or technique studied can be determined from the volumetric efficiency at specific times, the water costs derived from the quantity of electricity used, and the volumetric efficiency, as well as the costs of completing and converting the wells in a pattern. The development and water costs per barrel of oil produced are given in table 2. The 500-foot spacing contained 6.89 acres, whereas the 600-foot spacing contained 8.26 acres; the development costs per acre are also given in the table.

Figure 15 shows the relationship between volumetric efficiency and the cumulative input in percent of effective pore volume for patterns 2, 3, and 7. The spacing used on pattern 2 was 500 feet, whereas patterns 3 and 7 were flooded, using a 600-foot spacing.

Of all the patterns investigated, only the three most promising were analyzed by the graphic-form method shown in figure 15. The volumetric efficiency at break-through time is shown in the lower left corner of the graph. The straight line on the graph represents the total cumulative input

14/ Yuster, S. T., Water Flood Spacing: Producers Monthly, vol. 12, No. 1, Nov. 1947, p. 18.

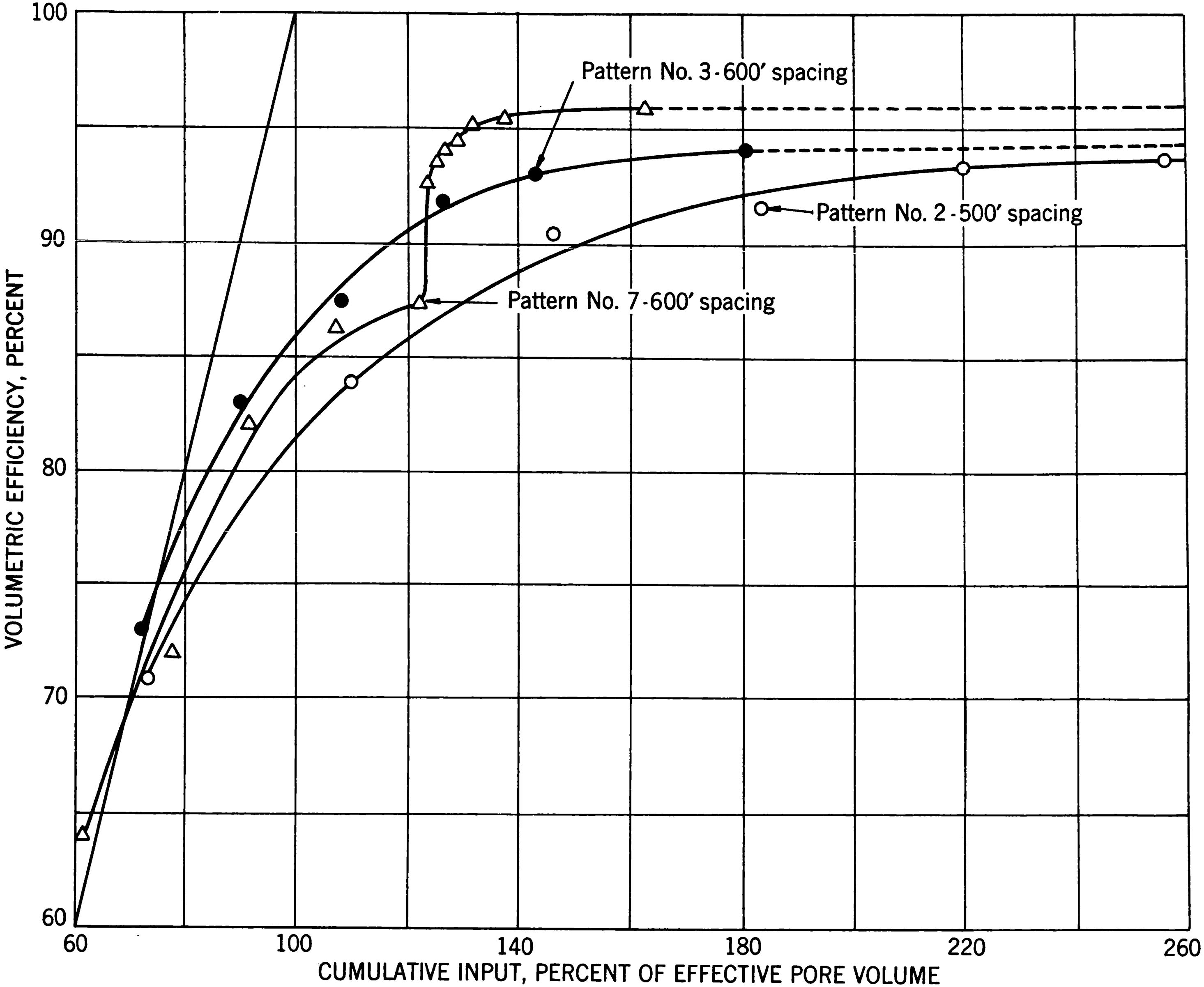

Figure 15. - Volumetric efficiency-cumulative input relationships of three patterns investigated in the electrolytic model study of water-flooding a shoestring sand.

at any time. The deviation of the flood-pattern curves from this line represents the amount of water being produced, because total fluid production equals total fluid injection.

The error, which is primarily human, introduced into the data by the calculations for both the volumetric efficiency and the cumulative input, is shown by the difference between the data at break-through and the straight line. The points should fall on the line; this error averages 2.8 percent for the three patterns shown, pattern 7 being largest, having 4.4 percent error at the break-through point.

To compare the efficiency of the two spacings, patterns 2 and 3 may be compared, because the transverse distance of the well positions in both patterns was equal. It can be noted that the efficiency at break-through increased 3.1 percent when the spacing was increased 100 feet (patterns 2 and 3, fig. 15). The 600-foot pattern theoretically would have recovered 2.9 percent more oil at break-through than the 500-foot spacing would be expected to recover with the use of 18.6 percent more water. The points that represent the same percentage of break-through time in patterns 2 and 3 (table 1) may be compared in figure 15. In all cases, the 600-foot spacing increased the volumetric efficiency at specific times.

Muskat's[15/] mathematical analysis of the efficiency of the staggered line drive has shown an increase in percent of total volume flooded at break-through time if the spacing is lengthened. Although the well pattern known as pattern 3 (fig. 7) is not a staggered line drive, it is quite similar in many respects and may be considered as a modified form of the staggered line drive.

The relative merits of patterns 7 and 3 should be compared, as they show the best possibilities of water-flooding a shoestring reservoir. Pattern 7 (fig. 11) in its final stage has the same well positions as pattern 3, but the type of well in that position has been changed. Figure 15 shows that the first stage of pattern 7 was not as efficient as pattern 3, but when the second stage of pattern 7 had been initiated, the volume of the pattern that was swept by the same amount of injected water was far greater than that swept by pattern 3. For example, when the cumulative input had equaled 140 percent of the effective pore volume in both patterns, pattern 7 had flooded 3.0 percent more of the pattern's volume. This means that more of the reservoir volume would have been exposed to the injected water for a longer period of input time in pattern 7 than in pattern 3; although the evidence indicates that all the patterns, with their different techniques, would eventually reach an efficiency of approximately 96.0 percent if they were continued to their appropriate amount of input time.

The other patterns (1, 4, and 9) from which enough data were obtained to plot into the form shown in figure 15 have been eliminated, either for low volumetric efficiencies or excessive costs.

15/ Muskat, M., The Flow of Homogeneous Fluids Through Porous Media: Second edition, J. W. Edwards, Inc., Ann Arbor, Mich., 1946, p. 594, sec. 9.28.

Figure 16 shows the relationships between costs (development and water) and volumetric efficiency. These curves again show the advantage the operator would obtain by water flooding the shoestring with a 600-foot spacing. In comparing patterns 2 and 3, it will be noted that of the costs studied, a barrel of oil may be produced for 7.0 cents less at break-through using the wider spacing. The curves of patterns 1, 4, and 9 have been extrapolated to the form followed by the curves of patterns 2, 3, and 7. All the curves turn upward in the later stages of all the floods, because a unit volume of water becomes less efficient as the flood progresses, and more water has to be injected to produce the same quantity of oil. The curves have been terminated at 96.0 percent volumetric efficiency, as it is believed that this is the maximum volume that could be flooded. At this point, the cost per produced barrel of oil would increase in a straight-line relationship. The volumetric efficiency at break-through time of each pattern is given in table 2. The volumetric efficiency at break-through time for pattern 9 does not fall within the limits of the graph in figure 16. It is a coincidence that pattern 2 (500-foot spacing) and pattern 4 (600-foot spacing) very closely approximate each other on these graphs. The figure shows that patterns 3 and 7 excell in having low costs at high volumetric efficiencies.

Figure 16 also shows the pre-eminence of pattern 7 over pattern 3, because the total volume of oil-bearing sandstone exposed to the water is greater in pattern 7. Therefore, the reservoir oil can be produced at a cheaper cost per barrel. It is estimated that when 95 percent of the field has been swept by the injected water, the cost of producing a barrel of oil would be 3.7 cents less with pattern 7 than with pattern 3. In other words, less water would be required to produce a similar volume of oil.

The authors have attempted to obtain a quantitative indication of the produced water:oil ratio. The following calculation was made with these assumptions: (1) No formation water was moved, (2) the volume of fluid produced equaled the volume of fluid injected, and (3) no water was produced until after break-through time had occurred. The volume of injected water that had to be produced was calculated from the total cumulative water input at the different volumetric efficiencies. The produced water:oil ratio (table 3) was obtained by dividing this volume of water by the volume of oil produced, as indicated by the volumetric efficiency. These ratios at different times during the flood's progress of patterns 2, 3, and 7 are shown in figure 17. It is realized that the data from which these curves were obtained are theoretical, and their value lies only in indicating the trend that the produced water:oil ratio should follow; but it is of interest to note the variations between the three patterns and the effect the second stage of pattern 7 has upon that pattern's water:oil ratio.

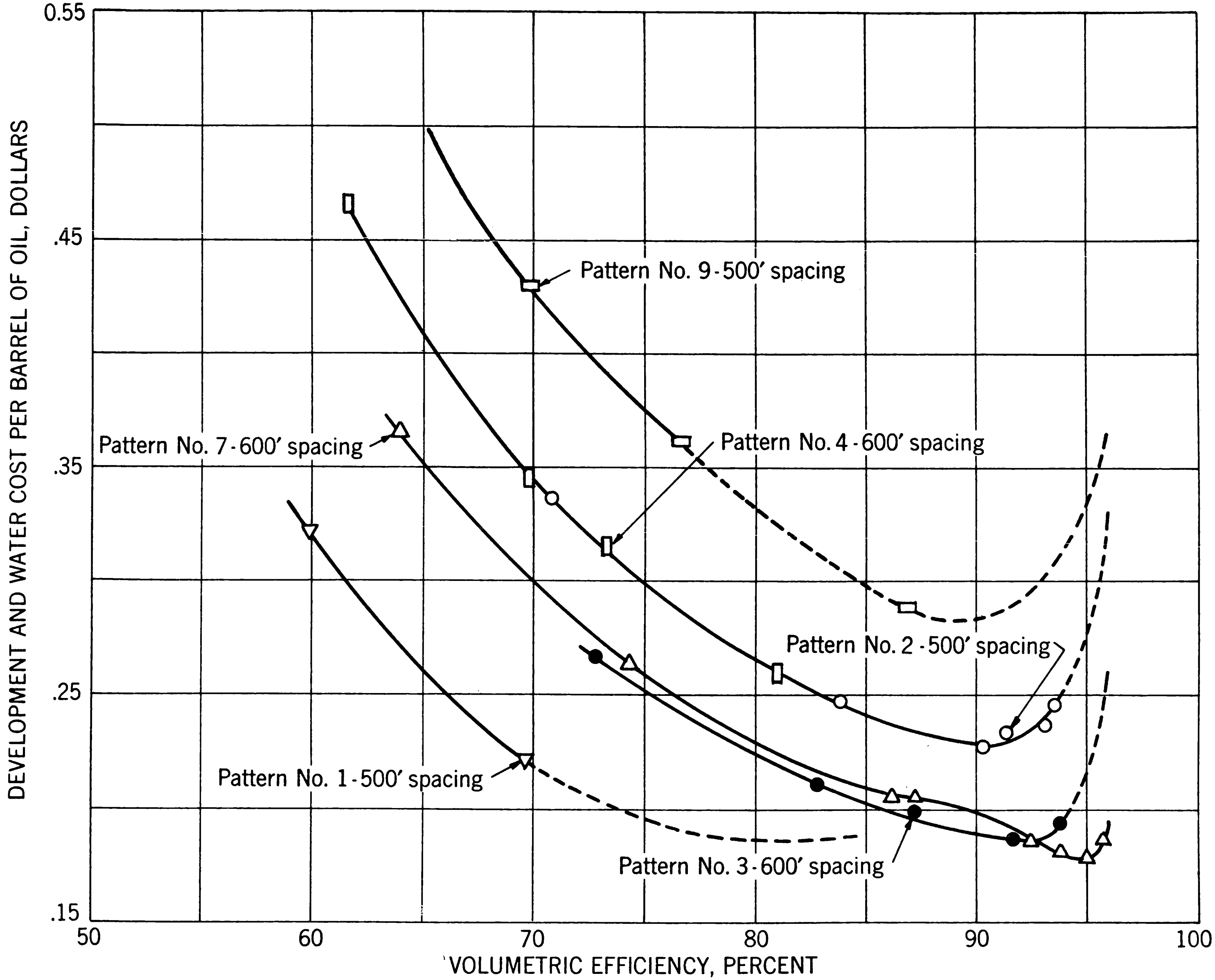

Figure 16. - Development and water costs-volumetric efficiency relationships of six patterns investigated in the electrolytic model study of water-flooding a shoestring sand.

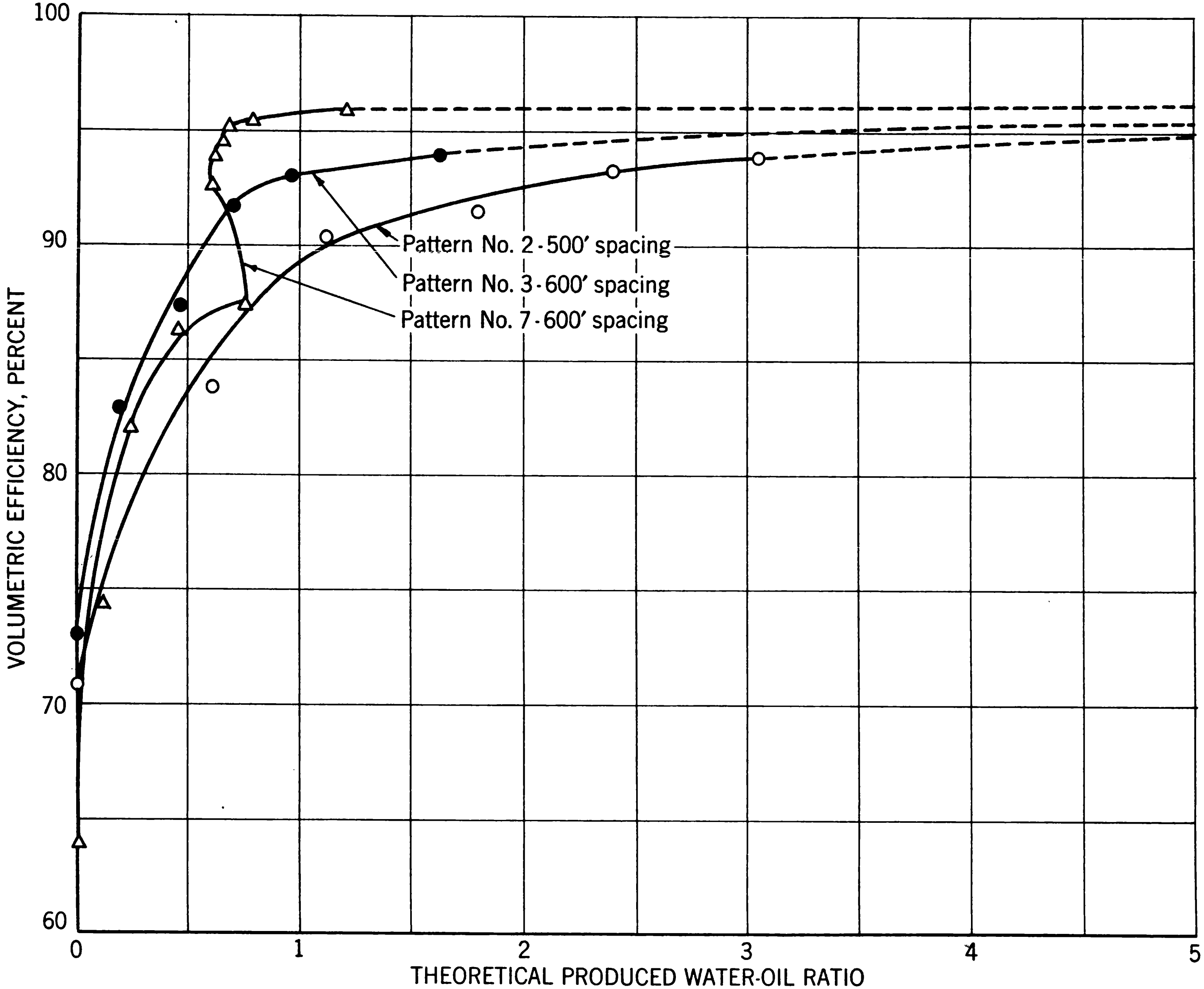

Figure 17. - Volumetric efficiency-water:oil ratio relationships of three patterns investigated in the electrolytic model study of water-flooding a shoestring sand.

TABLE 3. - Calculated produced water:oil ratio for patterns 2, 3, and 7

Pattern	Volumetric efficiency	Status of flood front, percent of break-through time	Theoretical produced water:oil ratio
2	70.8	100	0.00
	83.8	150	.60
	90.3	200	1.12
	91.5	250	1.79
	93.3	300	2.38
	93.7	350	3.04
3	73.0	100	.00
	82.9	125	.18
	87.3	150	.46
	91.7	175	.68
	92.9	198	.95
	93.9	250	1.62
7 (first stage)	64.0	100	.00
	74.4	127.2	.11
	82.0	150	.24
	86.3	175	.45
	87.3	200	.75
7 (second stage)	92.6	100	.60
	93.6	200	.60
	93.9	300	.62
	94.5	450	.65
	95.2	600	.67
	95.4	1,000	.78
	95.8	2,600	1.21
Total........	95.8	-	1.21

The question now arises as to when 200 percent of break-through time occurs in the first stage of pattern 7, or when, during the progress of the water flood, the operator should change his producing wells to injection wells as shown in pattern 7 (fig. 11). Assuming an injection rate of 2 barrels of water per foot of sand per injection well per day, and with the pertinent core data, the time scale for this flood was determined. The average sand thickness (23.4 feet) was calculated from the cross-sections shown in figure 2. The established injection rate was 93.6 barrels of water injected into the pattern per day. From table 2, 79,790 barrels of water was required to flood the pattern to break-through; therefore, 852 days, or 2.3 years, theoretically would be needed for break-through to occur in the first stage of flood pattern 7. Theoretically, then, 4.6 years would be the time required before changing the wells. The pattern should then be flooded until the operator realizes no profit from the water-flooding operation. In field operations the break-through time should not be greatly different from the calculated value unless there exists a conditon of excess by-passing. In this case the water:oil ratio will be excessive in the early life of the water-flooding project.

In evaluating the relative merits of the patterns studied to determine which would most efficiently and economically water-flood a shoestring sand, patterns 5, 6, 8, and 10 were eliminated from consideration because they had either low volumetric efficiencies when they were stopped or the cost per barrel of oil produced was high.

CONCLUSIONS

The rsults obtained from investigating these patterns and the derived data show conclusively that wider spacing between rows of water-injection wells increases the volumetric efficiency both at break-through and, thereafter, within the spacing limits investigated. The volumetric efficiency at break-through increased 3.1 percent when the spacing was increased 100 feet. This increase amounted to 9,537 barrels of oil above that which the similar shorter spacing would theoretically produce at break-through time. Development and water costs per barrel of oil produced at break-through were less by 7.0 cents when the spacing was increased from 500 to 600 feet.

Although the time needed to flood a longer spacing increases as the distance between input and output wells increases, the profit obtained by water-flooding a shoestring with the longer spacing should more than compensate the operator for that extra time.

Of the patterns studied, the pattern and technique shown as pattern 7 (fig. 11) is best suited to water-flood a shoestring sand most effectively. This pattern has two stages, the first having alternate rows of two injection wells and two producing wells across the 600-foot width of the shoestring. The injection wells in the first stage are 213.2 feet apart; the producing wells are 316.0 feet apart, or 158 feet from the axis of the field. When the two producing wells were converted to injection wells and a central producer was drilled to initiate the second stage, the pattern took the form of a modified seven-spot flood pattern.