

POTENTIOMETRIC-MODEL STUDY
OF EDGE-WATER ENCROACHMENT INTO
THE SOUTH ELK BASIN OIL FIELD

BY

WARREN J. MASON

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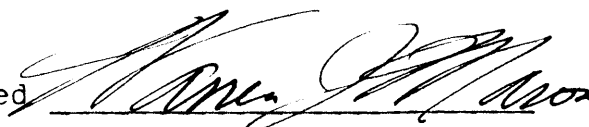
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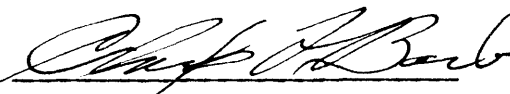
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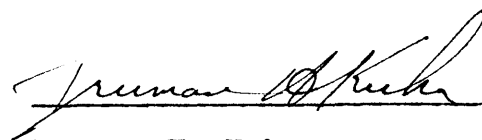
A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for degree of Master of Science.

Signed 
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INTRODUCTION

This dissertation covers the use and construction of a potentiometric-model for study of edge-water encroachment into the Tensleep pool of the South Elk Basin Oil Field. The study was made to try to establish the best production rate for each well so that the maximum amount of oil can be recovered by use of the natural water drive. As will be shown, by varying the rate of production in two experiments, the area swept out by the water drive is different.

Field Data

The Tensleep pool has approximately 520 proven productive acres. Development to date has outlined the structure, except for the southeast end of the field.

The structure is a small anticline with about 341 ft of closure above the oil-water contact, which is estimated to be at a minus 2300-ft elevation. Average net effective pay thickness is 76.6 ft. The Tensleep section is divided into seven zones which are separated by impermeable lime and sandy sections. Zone B was used for this thesis study, since there was insufficient time for the study of the other six zones.

Following are the weighted average reservoir characteristics for the Tensleep pool:

Porosity -----	14.2%
Average permeability -----	190 md
Initial datum pressure at minus 2155 ft -----	2493 psi
Connate water saturation -----	15.7%
Reservoir temperature -----	154° F
Initial formation volume factor -----	1.072
Initial oil viscosity -----	2.46 cp
Gas in solution in reservoir oil at initial conditions ----	124 std cu ft/bbl
Saturation pressure -----	753 psi

The reservoir originally contained a total of approximately 39,830 acre-ft of pay. Original stock-tank oil in place is estimated to have been 34,450,000 bbls with 4,272 MMcf of solution gas. A total of 1,601,410 bbls of stock-tank oil and 194 MMcf of gas has been produced up to December 1, 1949. The datum pressure has declined from the original pressure of 2493 psi to 1930 psi. For each pound drop in formation pressure, 2,844 bbls of oil has been produced. The Tensleep reservoir has a water drive which should result in an estimated water influx of 2000 bbls per day when the reservoir pressure is 1800 psi, and possibly as much as 4000 bbls per day when the reservoir pressure is 1500 psi. The estimated ultimate recovery of the tank oil is 13,469,000

bbbls from the productive area.

Object of Investigation

The most significant phase of this study concerns the production rate for each well so that the maximum amount of oil in place will be recovered. To accomplish this purpose, special equipment had to be built for the laboratory study. The description of this equipment and its use is given later in this thesis.

Another phase of this study was to plot an isobaric map of the field from the known pressure at each well. This plot was made with the equipment used for the study of the water encroachment of the pool.

Special Photographic Method

The maps of the flood outline for each experiment are shown by a simple photographic illustration. The original map, which is drawn directly from the electric field in the model, is reduced in size on tracing paper, and a pattern of the remaining oil in place is cut out of black paper. The pattern is placed under a map of the field and over a light table, then a picture is taken. This method saves considerable time in that only patterns will have to be drawn and cut out, and the whole field picture will not have to be drawn for each experiment. The resultant photograph gives a more realistic picture of the remaining oil and its position in the formation.

Acknowledgments

The writer wishes to acknowledge his indebtedness to Mr. C. C. Frye, Regional Petroleum Engineer, Continental Oil Company, for the information and permission to use the data on the South Elk Basin oil field.

Sincere appreciation is expressed to Mr. C. F. Barb, for the use of a room to set up the equipment and for the facilities of the petroleum shop.

The writer extends his gratitude to the physics and geophysics departments for providing meter equipment necessary to carry out this investigation.

THEORY AND APPLICATIONS

The flow of fluids through the porous media which constitute the underground fluid reservoirs is of considerable practical interest since the production of water, oil, or gas from tapping the sources depends upon such flow. It is desirable that the detailed behavior of such fluids be known in order that the wells may be handled in the most advantageous manner. It is well known that these underground porous strata are not homogeneous; therefore, no exact analysis may be made in practice.

Experiments indicate that at low velocities, porous flow is purely viscous, with a gradual transition toward turbulence as the velocity exceeds a critical value for the particular medium. However, the permeabilities of the porous media encountered underground, are so low that any departure from purely viscous flow involves pressure gradients which are out of the range ordinarily encountered. Thus in these problems, it may be said that the flow of inelastic fluids obeys Darcy's law, the velocity being proportional to the pressure gradient.

Hydraulic Flow vs. Electrical Current

The laws governing the flow of fluids through porous media are well known and are discussed in detail by Muskat (pp 140-572, 1937). Since the mathematical solution of these problems, and the problems in this thesis, are impossible, two idealized arrangements of injection and extraction were done to give an idea of the area invaded and then for only the simplest of boundary conditions. For a more complicated condition, such as water encroachment, the only practical approach is through the use of a model on a reduced scale. This model need not actually employ porous medium and a fluid. As Muskat pointed out there is under certain assumptions, an exact analogy between the flow of fluids in a porous medium and the flow of electrical current in a conducting body of similar geometry.

If the following assumptions are made,

1. permeability of the porous medium is uniform through out the reservoir,
2. relative permeability effects are neglected,
3. the viscosity difference of the driven and driving fluids is neglected,
4. gravitational effects caused by different density of the two fluids are neglected,
5. compressibility of the fluids is neglected,

then the electrical analogy of the hydraulic system is established wherein electrical currents proportional to the encroachment and the extraction rates are passed through a

conducting body by means of electrodes for wells, and a copper ribbon electrode for the oil-water contact. Under such conditions, the potential distribution in the conductor is exactly analogous to the pressure distribution in the field, and the current lines correspond exactly to the flow lines in the field. The study of fluid flow in an oil field is thus reduced to a study of current flow in an electrical conductor of the same shape.

Basic Equation

As already mentioned, the direction of the current flow at any point in the pool is identical with the direction of the fluid flowing at the corresponding point in the actual field, and the potential gradient at any point in the pool is proportional to the pressure gradient at the corresponding point in the field. Any element of fluid in the field follows a path corresponding to a current line in the pool. The transit time (dt) of an element or particle of the fluid from one point to another is proportional to the line integral of the inverse of the pressure gradient times the differential displacement along the current line. This relation can be shown as follows:

Velocity of flow $\sim dx/dt$

Velocity of flow is also directly proportional to the pressure gradient

Therefore, $dx/dt \sim \partial p / \partial x$

From this the expression for the transit time can be written

$$\left(\frac{\partial x}{\partial p} \right) \cdot dx$$

From the discussion given above, the equation for the transit time along a current line in the pool can be written

$$\left(\frac{\partial x}{\partial v} \right) \cdot dx \quad (v \text{ is voltage})$$

The problem of mapping the progress of an interface between the driving and the driven fluids is essentially the problem of determining these integrals along all the current lines in the electrically conducting pool.

Example of Application of Line-Integral Equation

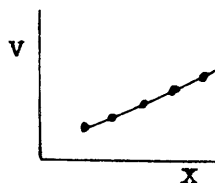
The high precision with which a measurement of the interface can be accomplished is recognized, but the method has not been employed extensively because the means for obtaining the integral have been too laborious for a practical application (Wm. Hurst and G. M. McCarty, 1941).

Hurst and McCarty Method: Step 1. The system of equipotentials in the conducting model is mapped against a set of rectangular coordinates by means of a probe connected to a potentiometer.

Step 2. The location of the equipotentials is plotted against a similar system of coordinates superimposed on a map of the field.

Step 3. The current lines are constructed graphically by drawing a system of curves which intersect the equipotentials at right angles.

Step 4. From the resulting map a chart is plotted for each current line, showing the electrical potential as a function of distance along current line.



Step 5. Each curve resulting from step 4 is differentiated graphically, and a new chart is plotted for each current line showing the derivative of length with respect to potential as a function of distance along the current line.

Step 6. The area under each curve resulting from step 5 is integrated with a planimeter, and a new curve is drawn for each current line showing the integral as a function of distance along the flow line. The ordinates of this last curve are proportional to the transit time between any two points read along the abscissa.

The plotting and calculation in the above steps for each current line could consume many hours of work, because it is possible to have hundreds of current lines on each map.

According to B. D. Lee (p 44, 1948), the method can be simplified by using a pantograph swiveled at the center, with the probe at one side and a marker at the other. With this pantograph the equipotentials are plotted directly on the map.

The drawing of curves for each current line can be omitted because the transit time along a flow line can be obtained from the difference equation,

$$\Delta t \sim (\Delta x / \Delta v) \Delta x$$

providing Δx is small compared to the size of the current line. If Δv 's are made the same by constructing equipotentials which differ by one, then

$$\Delta t \sim (\Delta x)^2$$

or, the transit time between successive equipotentials is proportional to the square of the distance between the equipotentials.

Exploring Foot Method

Each study involves a considerable amount of time, even by using the simplified method, in mapping the equipotential lines, constructing the flow lines, calculating the incremental transit lines along the flow lines, and then determining the boundaries of the invaded area.

B. D. Lee (p 58, 1948), states that the four-probe array can replace the single probe of the potentiometer, and is used to plot streamlines (flow lines) directly. Since, the single probe plots only the equipotentials lines, flow lines have to be constructed perpendicular to the flow lines; therefore the accuracy is dependent upon the operator. By the use of the four-probe array, the streamlines are plotted on the field map directly.

The array is made by mounting four probes in a small square of plastic, with the probes placed at each corner

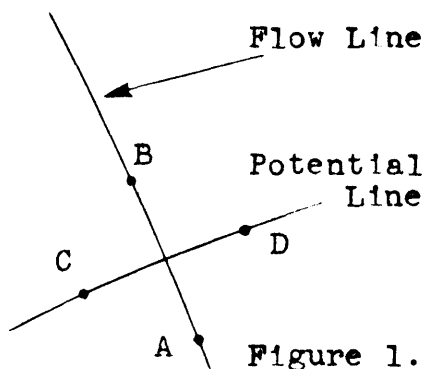


Figure 1.

of the square. The diagonal spacing of the probes was made one centimeter for ease of calculation, as will be shown. For very small models, the diagonal spacing should be less

for greater accuracy. These probes constitute an "exploring foot" which is placed in the conducting pool, and are mounted so that they turn along the vertical axis through one of the probes, such as probe A in Figure 1. A null

indicator can be connected between C and D, and the entire array can be rotated until this indicator registers zero volts. In this position the diagonal AB is then perpendicular to the potential line. If a very small scale voltmeter is placed between the probes A and B, the potential gradient can be read. Using the difference equation

$$\Delta t \sim (\Delta X)^2 / \Delta V$$

it will be realized that in the system now described, all the ΔX 's are equal so that the transit time from A to B is proportional to the reciprocal of the voltage difference between the points A to B. Streamlines are plotted with the incremental times recorded as the plot is made.

The isocronal lines can be drawn through the points of equal sums of increment times. These isocronal lines show the positions of the oil-water contact as the water invades the field.

LABORATORY APPARATUS

The apparatus used in these experiments consisted of a plastic model for the pool, with electrodes for the wells, and a copper band for the oil-water contact. A plotter with a means of support for the four-probe array was made in the form of a large T-square, which was movable along the Y-axis. The X-axis of the plotter was movable between two grooved supports, or guides, on the large T-square. Provision is made for the four-probe array to be in the pool while a two-foot array is supported over a map of the field.

An electrical panel board was built for feeding the proper voltages to the well electrodes and the copper band. A meter with a switching mechanism was used with the four-probe array to make it easy to indicate nulls on probes C and D, and to read potential gradients between probes A and B.

Plotter Construction

The picture of the plotter is shown in Figure 2. The guides for the center sliding bar are grooved and are

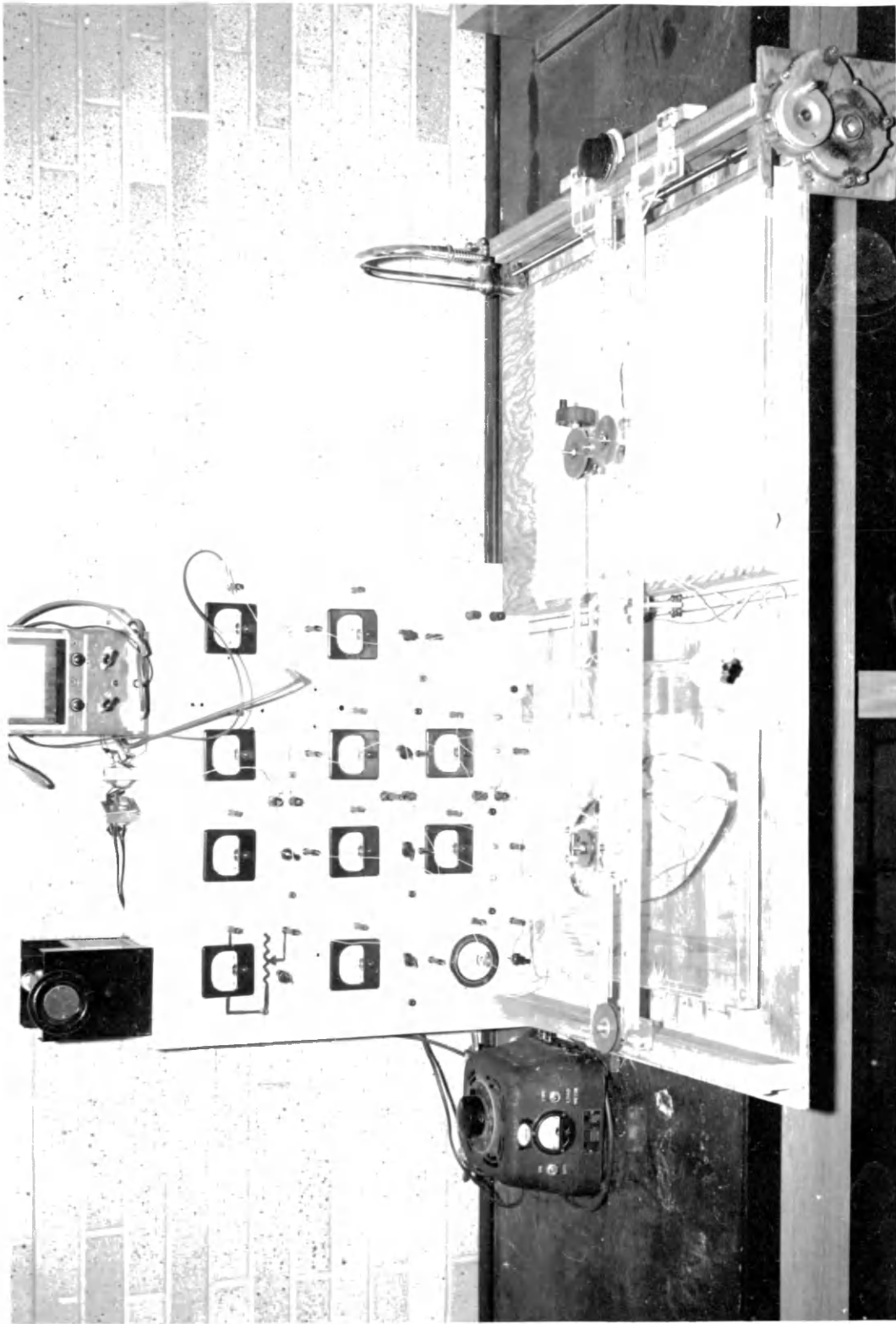


FIGURE 2

made with meter sticks and sheet plastic. It is important that the center bar move easily without any side play; otherwise the field lines in the pool would not be the same as the field lines drawn on the map. Play can be removed by placing on the side of the slider a strip of spring steel which fits inside the grooves of the guides. The guides are mounted on a right-angle support at one end, and ball-bearing wheels on the other. The right angle support, which supports the guides, is made of plastic and wood and is mounted on a raised side of the plotting table. Provision is made for the right-angle mount to fit over a hexagonal nut, which in turn is mounted on a long threaded screw. Rotation of the threaded screw, which moves the whole plotter along the Y-axis, is accomplished by a gear train box out of a Gibson Girl SOS transmitter. The gear train makes it very easy to move, with very fine adjustments, the points in the pool and over the field map.

The center bar, which supports the exploring foot and the map-plotter foot, is made of 1/4-in. sheet plastic. On one end of this bar is mounted a vertical shaft which supports the exploring foot. On the other end is mounted the map plotting points, which are also mounted on a vertical shaft. On each shaft is a worm-driven gear which is connected to a round, 3/8-in., solid plastic rod. The center bar is moved on the X-axis by means of radio-dial cable. The cable is attached to each end of the center

bar and around a vernier radio dial for ease of X-axis adjustments.

The whole plotter is supported over a large sheet of plywood. One side of the plywood sheet is a raised platform for the field map, and on the other side is a depression for the plastic pool.

Plastic Pool Model

The plastic pool is made of $1/8$ -in. sheet plastic. The depth of the pool is determined by the area of the field to be plotted and the size of the electrodes. If the electrodes are large in diameter, the depth can be small because the contact resistance between the electrode and the liquid would be small. For this study the depth of the liquid was $3/4$ -in., and therefore, the sides of the plastic model was $1\ 1/4$ -in. deep. Electrodes, representing the extraction wells were made of $1/15$ -in. diameter copper wire that passed through the model bottom. These electrodes are carefully sealed into the tank to prevent leakage of the electrolyte. Electrical connections can then be made to the electrodes on the underside of the tank. A copper strip $1/4$ -in. wide and $1/1000$ -in. thick is used for the oil-water contact. A wire is passed through the bottom of the tank and soldered to the copper strip.

Electrolyte

An electrolyte of relatively low conductivity is

desirable to minimize the effect of the contact resistance between the electrodes and the electrolyte. The composition of the electrolyte used is as follows:

Stock solution:

15 gm copper sulphate (anhydrous)
5 gm sulphuric acid
5 gm ethyl alcohol
100 gm distilled water

This stock solution is diluted with distilled water in the ratio of 1 part stock solution to 50 parts water.

Electrical Circuits and Meters

Panel Board: The electrical circuits, Figure 3, for the extraction wells and the oil-water contact were mounted on a panel board. The circuit diagram shows a voltage regulator on the input side of the 60-cycle line. This regulation is necessary because a slight variation of voltage on the electrodes will cause a shift in the equipotential lines. This shift will give a considerable error in the calculation of the isocronal lines.

Four-Probe-Array Switch: A double pole double throw switch was used for switching the four-probe array from probes A and B to the probes C and D. Very flexible wire is used for these connections because they have to be mounted and carried by the movable plotter.

Null Indicator: When the single probe of equipotential line measurements or the four-probe for flow line measurements is used, nulls on some type of a meter

must be found. Barring pickup and phase shifts, this minimum would have been zero, but in most measurements this was seldom realized. To overcome this disadvantage, a null indicator was constructed which could have threshold adjustments which were set to remove the residual voltage effect when a minimum was reached. The circuit diagram of this null indicator is shown in Figure 5. By adjusting the input voltage against the negative potential on the grid of the second half of the tube V_2 , the meter will indicate a maximum reading for a minimum signal input on the grid of the first stage.

Potential Gradient Meter: The meter used for measuring the potential gradient between the probes A and B was a commercial electronic voltmeter made by Ballantine Laboratories, Boonton, New Jersey. Specifications of the meter, Model 310 A, are as follows:

Voltage range: Direct reading from 100 microvolts to 100 volts in 6 decade ranges.

Frequency range: 10 cps to 2 mc for voltage measurements.

Input impedance: 2.2 megohms at 60 cps.

Accuracy: In range 100 microvolts to 100 volts, 3% from 10 cps to 1 megacycle per second.

It is important to use a meter with a low voltage scale and a high input impedance because very small voltages are encountered when potential gradient measurements are made.

Current Meter: The electrical panel-board circuit

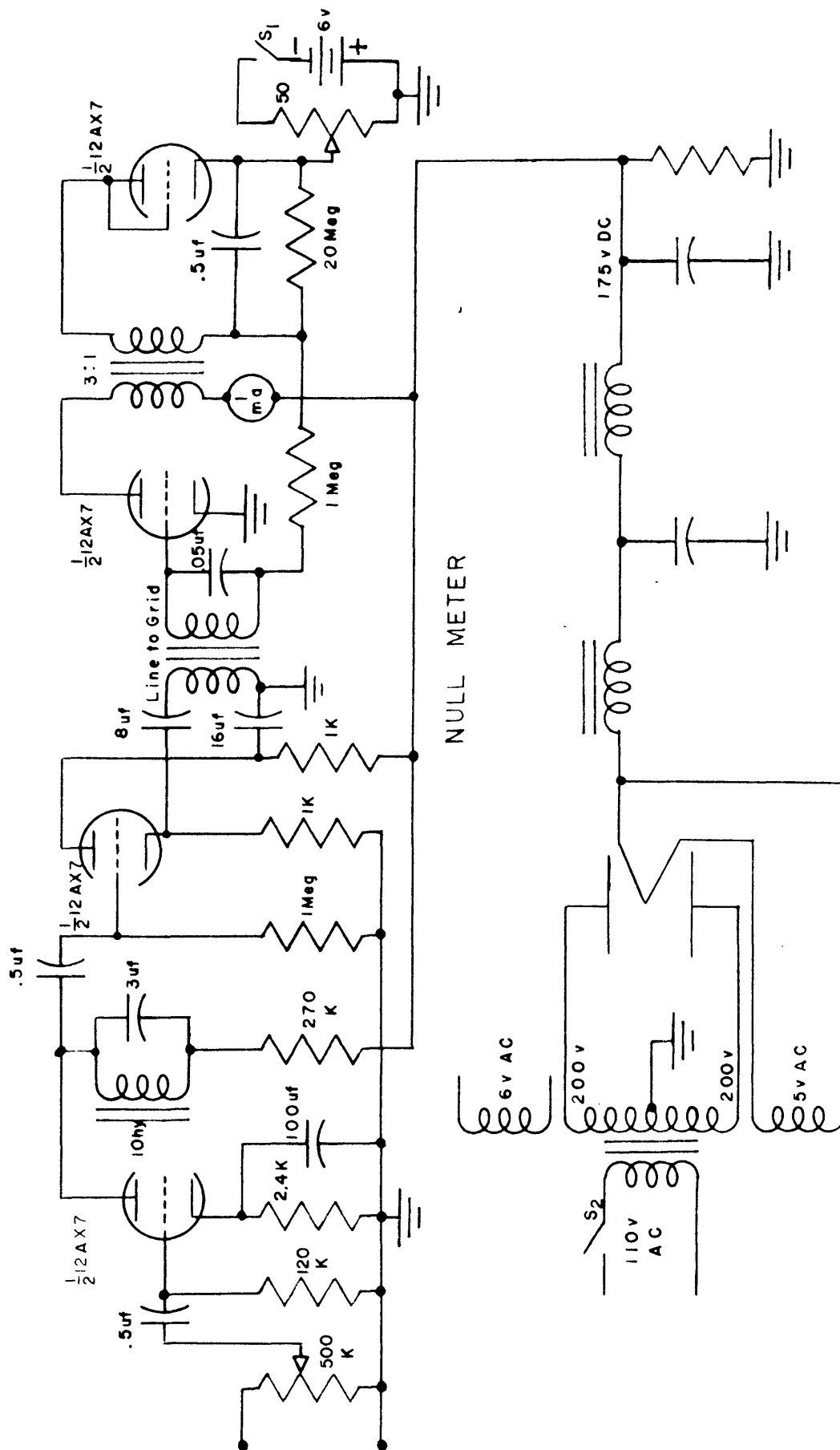


FIGURE 5

diagram shows a 100-ohm resistor is in series with each 25,000-ohm variable resistor. The current to each electrode can be measured by reading the voltage across the 100-ohm resistor. This voltage is measured with an electronic voltmeter which will not load the circuit when placed across the resistor. Loading of a circuit would cause the current in the electrode to be different from that actually in the circuit when the meter is removed. Current in an electrode is found by multiplying the voltage across the 100-ohm resistor by 10, a calculation which gives the current in milliamperes.

OPERATION OF EQUIPMENT

Discussion is given in the following sections of the operations of plotting equipotential lines with the single probe, and of plotting of current lines with the four-probe array.

In operation, it is important that the current to any electrode be kept low enough to avoid formation of gas bubbles on the electrodes. Formation of bubbles raises the contact resistance and causes a shift of equipotential lines. In these experiments the maximum current used on any one electrode was not larger than 25 ma. For the size of the electrodes and the electrolyte conductivity, it was found that 30 ma per electrode could be tolerated without any effect from gas bubbling.

Single-Probe Plotting

Current to the electrodes was supplied from two filament transformers, which were wired in such a manner that 110 volts on the line side were isolated from the 110 volts on the load side. All electrodes representing producing

wells were connected through the 25,000-and 100-ohm resistors to the transformer. The voltage to each electrode was adjusted to correspond to the bottom-hole pressure for each well in the field. The values of these voltages and corresponding pressures are given in Table 1.

Table 1

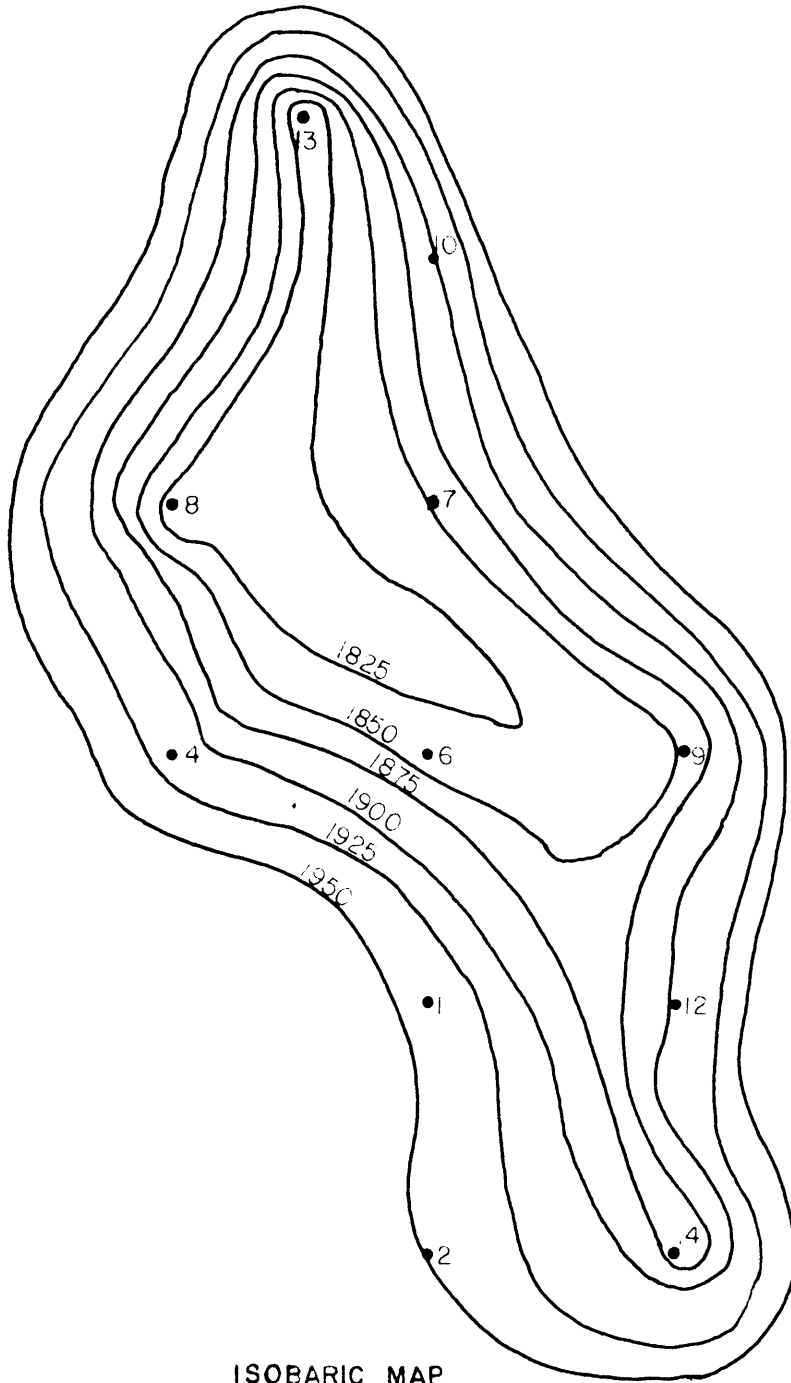
Well No.	BHP psi	Voltage on Electrode
13	1800	0.00
8	1821	8.18
6	1836	14.60
7	1846	18.60
9	1846	18.60
14	1854	22.00
10	1899	40.00
12	1904	42.00
4	1909	44.00
1	1939	56.00
2	1948	60.00

A potentiometer, consisting of two decade resistance boxes, was then connected between two electrodes. In practice it is best to use the electrodes of maximum and minimum potential; therefore in this study electrodes 13 and 2 were used.

Probe A on the four-probe array, with its tip immersed in the electrolyte, was used to explore the pool. This probe was connected to the input of a 60-cycle band-pass amplifier, ground potential side of which was connected to the junction of the two decade resistance boxes, with the sum of the resistances of the two boxes maintained constantly at 6,000 ohms. By adjusting the ratio of the two boxes, the potential of their common point was set for the potential of the equipotential line to be plotted. When the probe is placed at a point of potential equal to its own potential, the input signal to the null indicator is at a minimum. Once a point is found in the pool equal to this potential, a sharp-prick punch, mounted on the two-foot array, was depressed to mark a point on a sheet of paper on the map board. The probe was then moved to other null points, marking their positions on the map until sufficient points had been obtained to permit construction of the equipotential line. Figure 6 shows the result of a equipotential map for the values given in the table on page 22.

Four-Probe-Array Plotting

Current to each electrode is adjusted to represent the relative production of each well. The current in the copper band, which represents the water encroachment, is equal to the total current of the 11 producing wells. This copper band was connected to the zero side of the isolation transformer.



ISOBARIC MAP

FIGURE 6

After the currents have been adjusted to the proper values, a map of the field is placed on the raised portion of the plotting table and is properly oriented with respect to the electrodes in the plastic pool. The exploring foot is lowered into the conducting pool and probe A is placed at the desired starting point, which is some point on the copper band, or a point on the boundary of a previously invaded area. The exploring foot is then rotated until probes C and D are on points of equipotential, as shown by the null indicator. Probes A and B are then on a current line, and the potential gradient reading is recorded on the map. The exploring foot is then moved so that probe A was made to occupy the previous position of probe B, and a new null and gradient read. A current line may thus be followed until it terminates on a producing well.

The above process was repeated for many such current lines, and the total transit time from the starting point to any point on a current line can be found by summation of the incremental times determined for each step. An isochronal line was then drawn through the points of equal time. When the isochronal line went through or touched a producing well, that well was turned off and the copper band was then made to conform to the new position of the oil-water contact. Without changing the currents to the remaining electrodes, the above steps were repeated until

a new isocronal line went through another producing well. The process was repeated until all wells in the field, except the last one, were turned off. The isocronal line, which then passed through the last well, gave the outline of the remaining oil left at the time water was just beginning to be produced by this last well. By varying the extraction rates for the producing wells, it was possible to change the final resultant picture of the oil left in the reservoir at the time of breakthrough on the last well.

Treatment of Data

The data in Table 2 on page 27 is for one current line, which existed between the current strip and one extraction well. This table shows the method by which the total time to a point on this current line was found. Other data for all the current lines are not given because of the numerous lines that were plotted.

Points	Potential Gradient	t	t
1-2	0.041	24.40	24.40
2-3	0.048	20.80	45.20
3-4	0.055	18.20	63.40
4-5	0.066	15.15	78.55
5-6	0.079	12.67	91.22
6-7	0.091	11.00	102.22
7-8	0.106	9.44	111.66
8-9	0.126	7.94	119.60
9-10	0.145	6.90	126.50
10-11	0.178	5.62	132.12
11-12	0.221	4.53	136.65
12-13	0.306	3.27	139.92
13-14	0.409	2.44	142.36
14-15	0.612	1.64	144.00
15-16	0.956	1.05	145.05
16-17	1.350	0.74	145.79
17-18	1.960	0.51	145.30

Table II

RESULTS

Figure 8 is a picture of the oil-water contact as determined by wells drilled into water on the boundary of the field. The results given by Figures 9, 10, 11, and 12 show the effectiveness of the natural water drive in recovering the maximum amount of oil before water is produced at the final well in the field. Figures 9 and 10 show the results of the drive by keeping the production from each well the same. Figures 11 and 12 show the results of the drive by allowing wells 2 and 14 to produce $2 \frac{1}{2}$ times as much as the others and also, by allowing wells 2 and 14 to produce until 100 percent water flows into their well bores.

The drive studied is essentially a line type; therefore, an experiment was performed to give a general idea of the pattern for a simple line drive.

Test I

This test was a line drive into one producing well. The drive was a straight copper strip, and the well was one electrode with a current of 10 ma being produced from the straight copper strip.

Figure 7 shows the results of this test at the time the incoming fluid, in black, first entered the well.

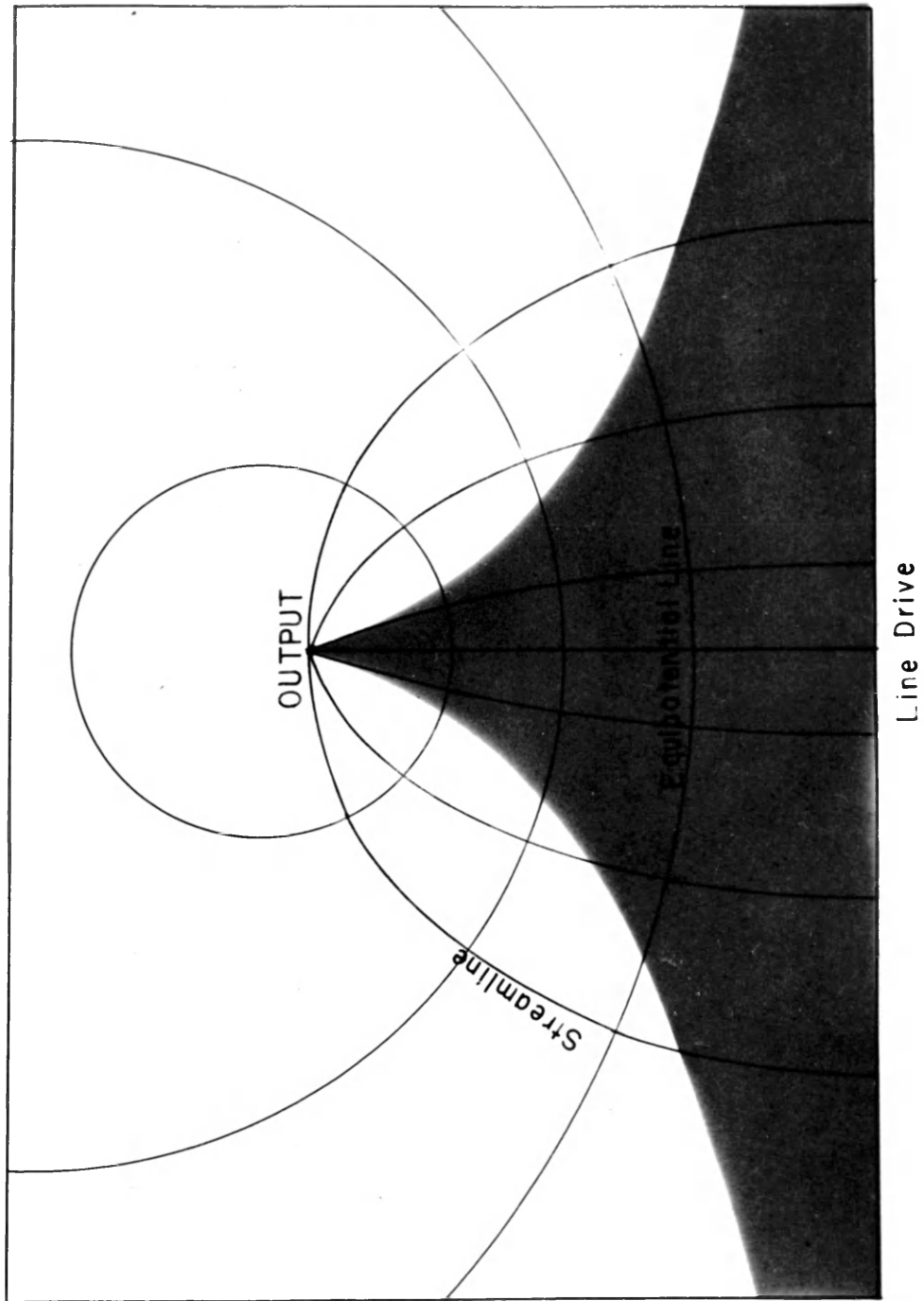


FIGURE 7

Test II

Figure 9 is a picture of an intermediate pattern of the oil-water contact during a time when the production from each well was the same. For this test the production from each well was adjusted to 10 ma.

Figure 10 is the final pattern of the drive when the last well just started to produce water. The percentage of oil left at the time of this breakthrough at well No. 6 is 11.4 percent.

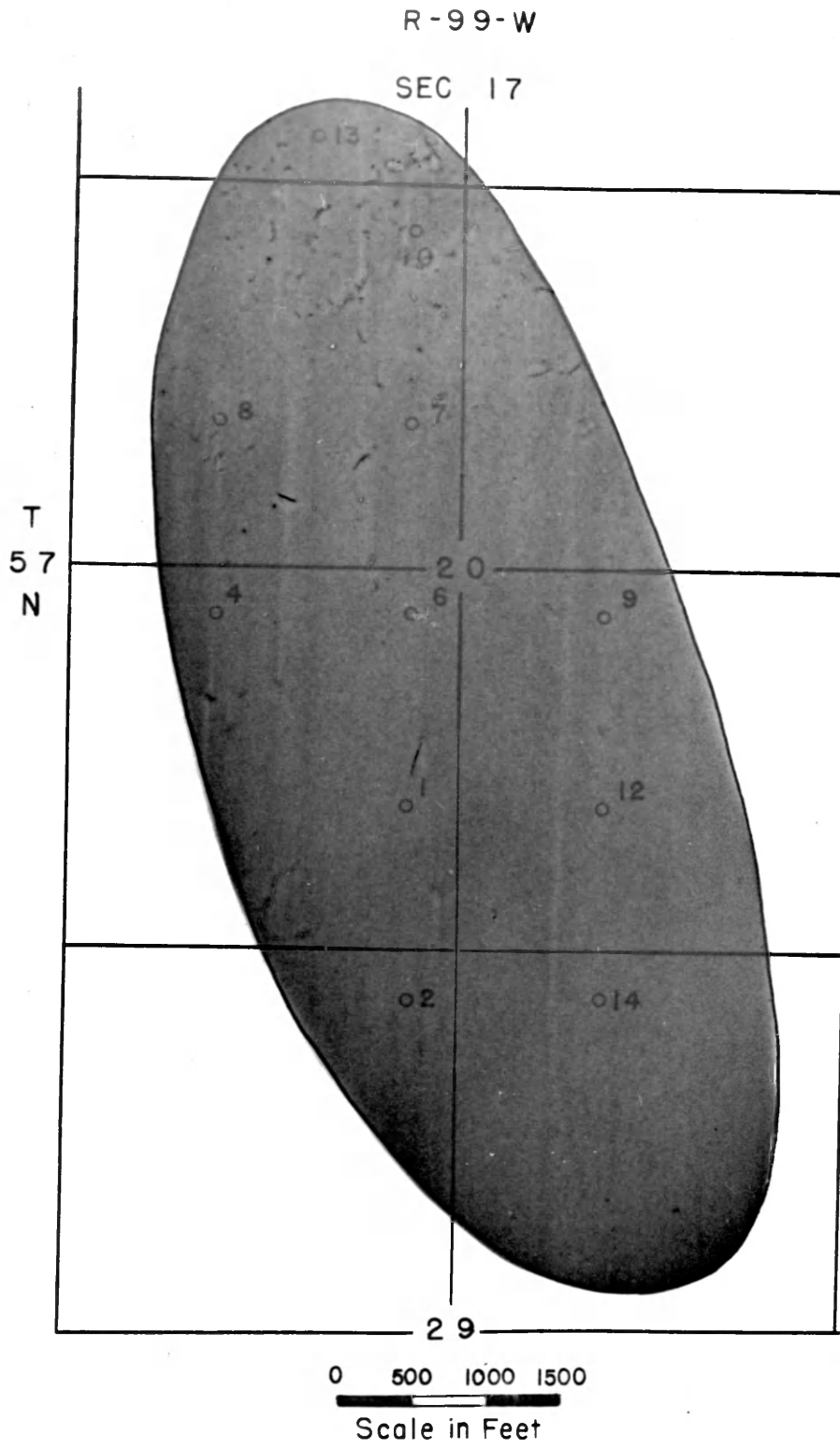


FIGURE 8

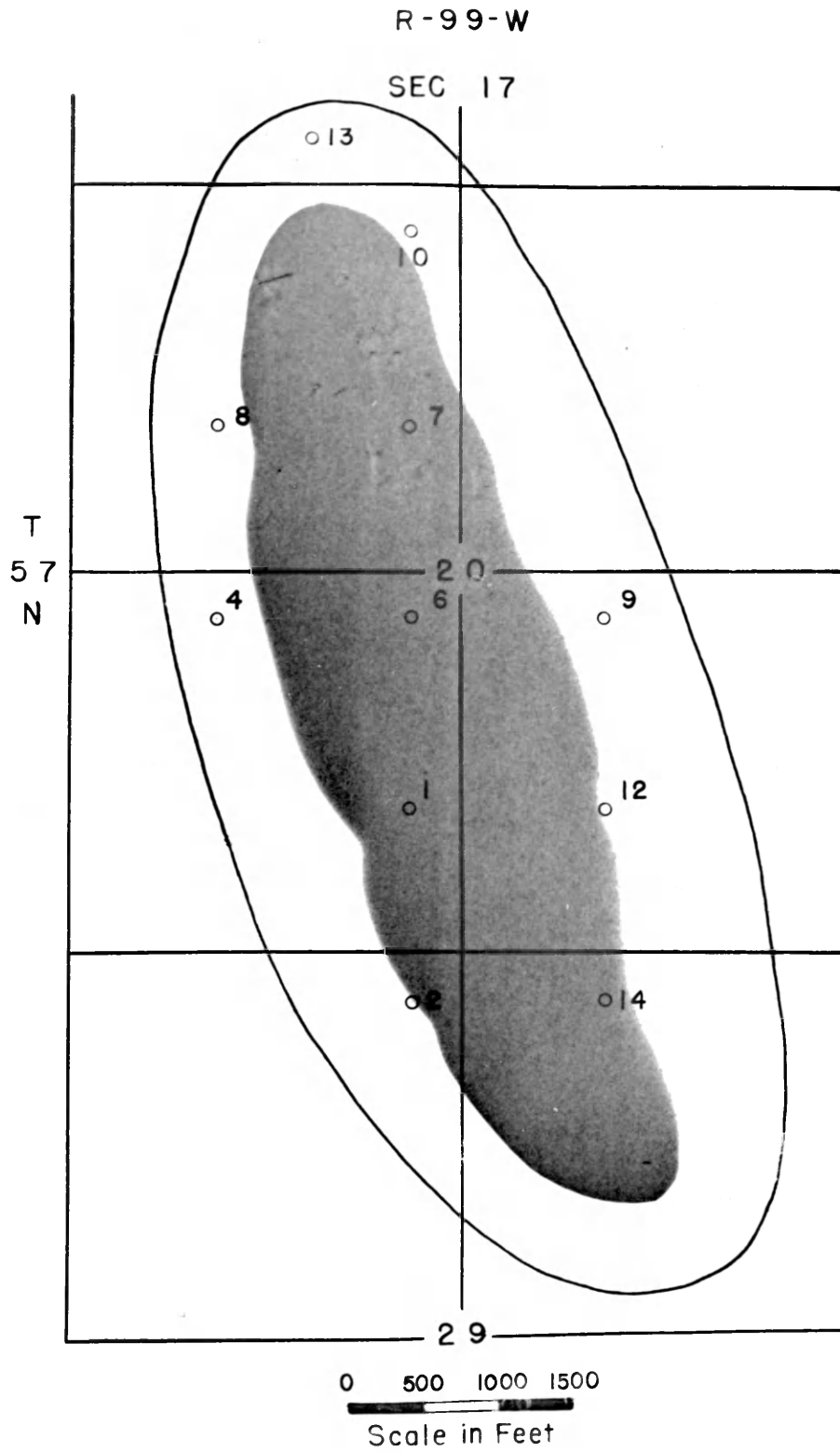


FIGURE 9

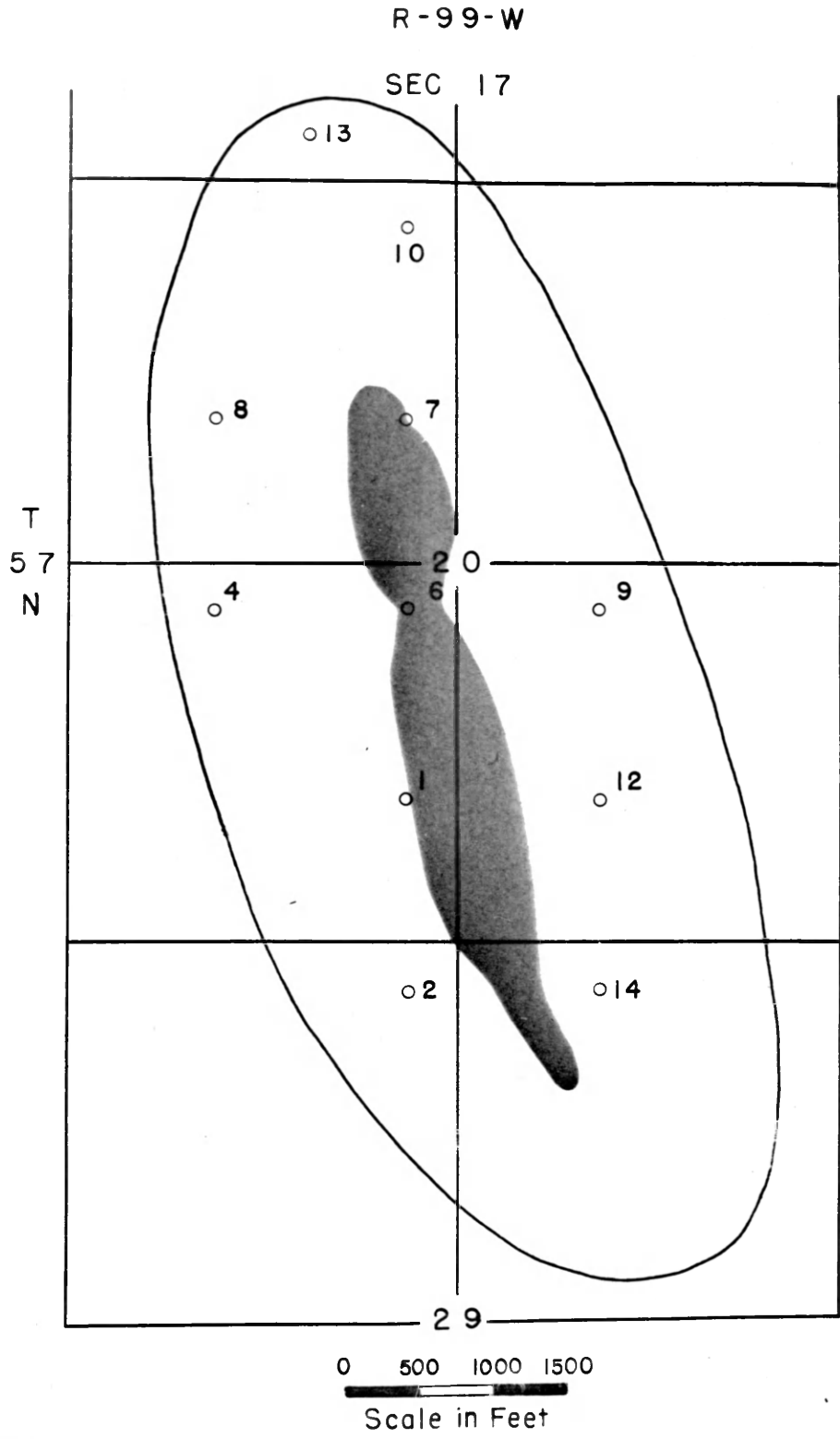


FIGURE 10

Test III

Figure 11 is a picture of an intermediate outline of the oil-water contact when the currents in wells No. 2 and 14 were adjusted to 25 ma each. Another condition imposed upon the production was to allow wells 2 and 14 to produce until 100 percent water was entering their well bores.

Figure 12 gives the picture of the oil in place at the time of breakthrough at the last well. This leaves 2.7 percent of the original oil in the formation, which means that more oil will be produced by the natural water drive. The lower percentage of oil remaining demonstrates the advantage of changing production rates for each well.

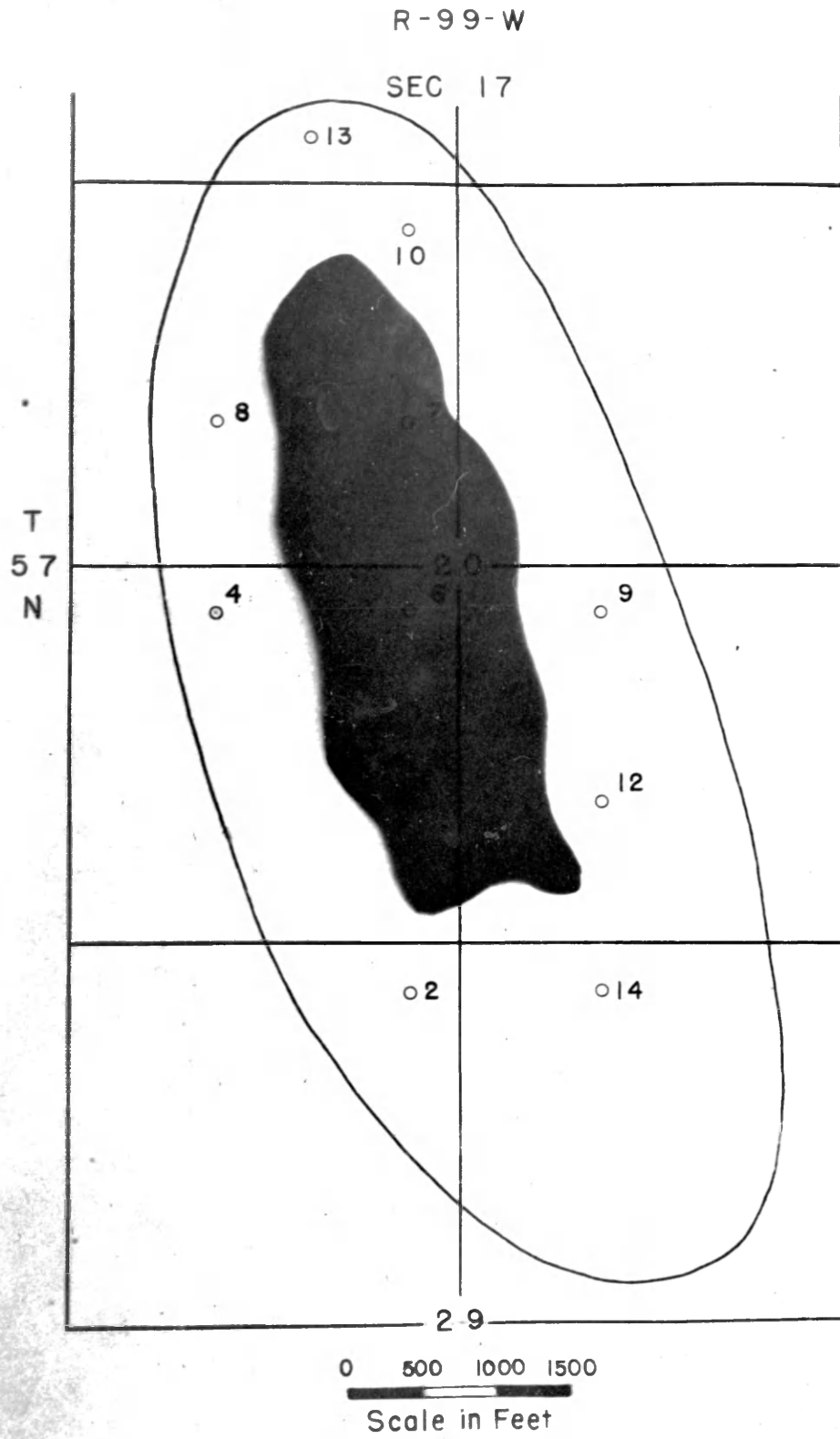


FIGURE 11

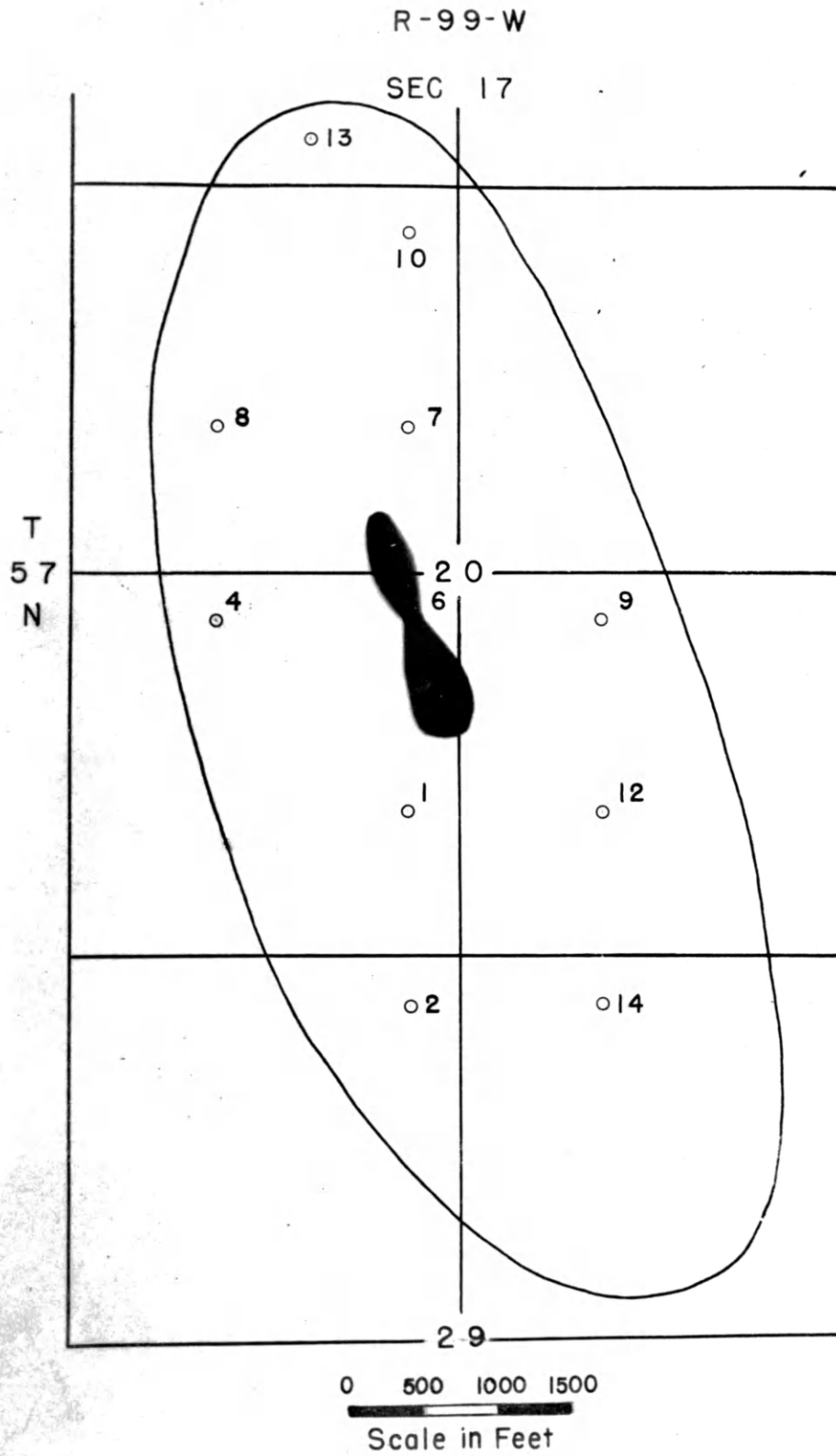


FIGURE 12

RECOMMENDATIONS

It should not be assumed by the reader of this thesis that the complete picture of the best way to produce the South Elk Basin field has been achieved. Many more tests should be made by varying the conditions of the production of the wells, and by taking into account the permeability and sand thickness changes throughout the field. Two major changes in the equipment should be made to make the study more accurate: a new plastic model should be constructed, and a device to add the sums of the incremental times of the segments of the flow lines as they are traced should be purchased.

A new plastic model should be built which takes into account the permeability changes in the field. This can be done by using the permeability given by the core data for each well. From this information a map can be drawn showing the lines of equal permeability throughout the field. From the isopac map of the field the thickness of the sand crossing the lines of equal permeability can be determined. The product of the thickness and permeability

at any point in the field can then be found, and a new map can be drawn, showing lines of equal products. By the use of information from this equal product map, a model can be constructed so that the depth of the electrolyte would correspond to the product of the permeability and sand thickness at any point in the field. By the use of this new model, more accurate final results could be attained because the depth of the electrolyte would correspond more closely to the conductivity of the formation as it exists.

If these two changes were made, a much better picture of the natural water drive could be plotted. Time consumed in construction of the equipment did not permit the additional work that would be required, but since the major equipment is now available, it is recommended that the study of the field be continued.

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