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THE EFFECT OF VARYING VISCOSITY RATIOS ON
DISPLACEMENT OF OIL BY WATER IN POROUS MEDIA WITH
CONNATE WATER

By

CHARLES THOMAS EVANS

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THE EFFECT OF VARYING VISCOSITY RATIOS ON
DISPLACEMENT OF OIL BY WATER IN POROUS MEDIA WITH

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CHARLES THOMAS EVANS

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THESIS AND ABSTRACT APPROVED:

Radislaus Fila

Thesis Adviser

R E Herr

Faculty Representative

H. H. E. E.

Dean of the Graduate School

283424

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Symbols and Abbreviations

A	cross-sectional area, square centimeters
AC	alternating current
cc	cubic centimeters
cp	centipoises
C_w	calibration constant determined with water
$^{\circ}\text{F}$	degrees fahrenheit
f_w	fraction of water in flowing stream
Fig.	figure
K_o	permeability of sand to oil
K_w	permeability of sand to water
pH	negative logarithm of the concentration of the hydrogen ion, in gram atoms per liter
psi	pounds per square inch
Q	cumulative pore volumes injected, cubic centimeters
Q_t	total amount of water entering the system, cubic centimeters
q_t	total rate of flow, cubic centimeters per second
S_w	water saturation
SAE	society of automotive engineers
t	time of efflux, seconds
T_a	absolute temperature, degrees rankine
u	distance along path of flow, centimeters
V_o	cumulative oil production
V_t	cumulative total production, cubic centimeters
V_w	cumulative water production, cubic centimeters
v_o	increment of oil production, cubic centimeters
v_t	increment of total production, cubic centimeters

v_w	increment of water production, cubic centimeters
v_o/v_w	increment of percent oil in efflux

Greek Letters

β	constant determined by design of instrument
θ	time, seconds
μ	viscosity, centipoises
μ_o	viscosity of oil, centipoises
μ_w	viscosity of water, centipoises
ρ	density, grams per cubic centimeter
ϕ	porosity

Chapter I

Introduction

As a result of the high percentages of oil left in an oil reservoir after primary recovery methods have been completed, it has become apparent that nature has provided an insufficient amount of energy to expel a major portion of petroleum originally in place. With the realization that petroleum deposits in the United States are approaching economic exhaustion, the petroleum industry has become increasingly active in finding methods for maintaining this energy where it has not been depleted and also methods for recovering oil left in place after the original energy has been depleted.

Water flooding had a late start as a secondary recovery method because the introduction of water into an oil sand was prohibited by law until around 1907 when the New York and Pennsylvania legislatures permitted the practice. Before this time very few details on water flood can be found because of the secrecy of the operations.

An estimated 100 billion barrels¹ or more of oil remain in fields discovered and produced. Of this, an estimated 7 billion barrels are recoverable by secondary recovery methods. Since the total national reserve has been estimated at 20 billion barrels² this has the effect of increasing our national reserves by approximately 35 percent.

Water flooding as a method of secondary recovery has received a great

¹ Torrey, Paul D. "A Review of Secondary Recovery in the United States," Secondary Recovery of Oil in the United States, 1950. Chapter 1, p. 1.

² "Mid-Year Engineering Economic Report," Oil and Gas Journal. (July, 1950).

deal of attention in the last few years, and a considerable amount of laboratory research has been made on this specific problem. It is hoped that this work, "The Effect of Varying Viscosity Ratios on Displacement of Oil by Water in Porous Media with Connate Water," will be of some use in the further development of the theory of fluid displacement during secondary recovery operations.

Chapter II

Review of Previous Investigations

The first actual analysis of the flow of fluids in a porous medium was done by H. D'Arcy, a French physicist in 1856. Due to the small velocities characteristic of flow through porous media the mathematical difficulty of applying the Stokes-Navier equations for the flow of viscous fluids in free vessels were practically insurmountable, so D'Arcy had to resort to an experimental study of the problem. The results of these experiments gave the simple result that the rate flow of water through the porous medium was directly proportional to the area of the sand and to the difference between the fluid heads at the inlet and outlet faces of the bed, and inversely proportional to the thickness of the bed.

This pioneering work and its application to the petroleum industry was overlooked during the early days of petroleum production, however, since 1920 considerable work has been done on the mechanics of oil production and a much clearer picture has been gained.

In recent years the trend of investigations has been toward a better understanding of reservoir performance with the conservation of reservoir energy being stressed and, where this energy has been depleted, with the application of secondary recovery methods. With the new techniques developed, the production of oil is becoming a more exact science rather than the trial and error methods used a few years back.

In 1926 Nutting³ conducted a series of analyses on movements of fluids in porous solids. In this work he analyzed only pores of tubular type. The

³ Nutting, P. C. "Movement of Fluids in Porous Solids." Oil and Gas Journal. (December 23, 1926), pp. 26, 125.

active force was taken as a resultant of capillarity, hydrostatic head, atmospheric pressure, pressure of trapped gases and the weight of the liquid itself. In order to check his formulas, Nutting conducted experiments on sand in a half-inch vertical tube.

Plummer, Hunter and Timmerman⁴ conducted a series of experiments in 1937 on the flow of mixtures of oil and water through sand. The arrangement of their core was to check the proportional flow of oil and water when the core was partially submerged in each, and to check the effect of decreasing the interfacial tension on coning of water in a core. They found that decreasing the interfacial tension caused the flow of water to almost stop.

Earlougher⁵ conducted a series of experiments on the relationship between velocity of displacing fluid, oil saturation, and flooding efficiency during water flooding operations by using actual cores taken from the field and he concluded that:

1. For any given oil saturation there is a critical maximum velocity above which the recovery efficiency by flooding falls off rapidly.
2. Recovery efficiency by flooding is largely dependent upon two factors; percentage of oil saturation at the beginning of the flood and the velocity of the flooding water.

Buckley and Leverett⁶ describe the mechanism of fluid displacement in sand as occurring in two distinct phases, the initial stage where the dis-

⁴ Plummer, F. B., Hunter, J. C. and Timmerman, E. H. "The Flow of Mixtures of Oil and Water Through Sand." Oil and Gas Journal. (April 8, 1937).

⁵ Earlougher, R. C. "Relationship between Velocity, Oil Saturation and Flooding Efficiency", Transactions, American Institute of Mining and Metallurgical Engineers, Petroleum Division, (1943), 151, 125.

⁶ Buckley, S. E. and Leverett, M. C. "Mechanism of Fluid Displacement in Sands." Transactions, American Institute of Mining and Metallurgical Engineers, (1942-1943), Vol. 146, pp. 107, 123.

placing fluid is almost 100 percent effective and the subordinate phases during which the permeability of sand to oil will continuously decrease and the permeability of sand to water will continuously increase, until during the latter stages of displacement large volumes of displacing fluids will only effect slight removal of additional oil. In their article, Buckley and Leverett have worked out a theoretical method for calculating the distance the initial phase moves for a given quantity of injected displacing fluid and the saturation of the two fluids at a specified distance along the flood. Earlier work along this same line was done by Wyckoff, Botset, and Muskat⁷ who used an analogy between D'Arcy's law and the law of electrical conduction by means of which they set up electrolytic models.

A great many experiments have been run in the past without considering the effect of connate water, but Dickey and Bossler⁸ seem to think that the results of tests that do not include the effect of connate water cannot be applied to normal field operation.

Dunlap⁹ investigated the influence of connate water on permeability of sands to oil and concluded:

1. As water saturation exceeds approximately 15 percent of the pore volume, the permeability of sands to oil decreases rapidly.
2. Ultimate recovery could possibly be increased if methods could be devised to remove water from the sand immediately surrounding the

⁷ Wyckoff, R. D., Botset, H. G., and Muskat, M. "The Mechanics of Porous Flow Applied to Water-flooding Problems. Transactions, American Institute of Mining and Metallurgical Engineers. (1933) Volume 103, pp. 219, 249.

⁸ Dickey, Parke A. and Bossler, Robert B. "Role of Connate Water in Secondary Recovery of Oil." Transactions, American Institute of Mining and Metallurgical Engineers. Volume 155, pp. 175, 183.

⁹ Dunlap, E. N. "Influence of Connate Water on Permeability of Sands to Oil". Transactions, American Institute of Mining and Metallurgical Engineers. (1938) Volume 127, pp. 215, 225.

well.

3. It is possible that unconsolidated oil bearing sands with water saturations as high as 50 percent can produce 100 percent oil with no water.

There is some doubt in the authors' mind as to the direct applicability of this test to an actual reservoir since flow was vertically downward, high permeability sands were used, kerosene instead of crude oil was used, sands were unconsolidated, and distilled water was used instead of brine. The differences between experiment and practice appear secondary and the conclusions seem to be justifiable.

Schilthuis¹⁰ also ran some experiments on connate water in oil and gas sands and stressed the fact that utmost precaution should be used in consideration of connate water.

As it now stands, the effect of changing operation variables or the specific influence of operating parameters is still not fully understood. More experimental work will be necessary before accurate quantitative data will be available.

¹⁰ Schilthuis, R. J. "Connate Water in Oil and Gas Sands." Transactions, American Institute of Mining and Metallurgical Engineers. (1938), Volume 127, pp. 199, 214.

Chapter III

Statement of Problem

The object of this thesis is to show the effect of connate water on displacement of oil by water in porous media with oil to water viscosities varying from 1 to 1 up to 10 to 1. This range would cover most of the viscosity ratios actually found in practice.

The experiments were undertaken to try to obtain a correlation with work done by previous investigators who neglected the effect of connate water.

The information to be obtained was of fundamental nature and it was deemed advisable to keep as many variables constant as possible. These variables are viscosity of fluids, specific gravity of fluids, physical characteristics of the porous media, chemical characteristics of the porous media and differential pressure or rate of displacement.

Chapter IV

Experimental Apparatus and Material

The use of a synthetic core was deemed advisable in order to eliminate chemical reaction and to obtain a uniform porosity and permeability.

The sand used in the fabrication of this core was an outcrop of the oil creek formation obtained from the Sulphur Silica Company, Sulphur, Oklahoma which was made up of essentially pure quartz grains in its original condition. In preparing this sand for use in the core, it was first carefully sieved. Sand grains that passed through a 65 mesh screen and were caught on a 100 mesh screen were used for this core. The sized sand was then washed by jetting tap water up through the sand, this was done until the water efflux was reasonably clear. The sand sample was then washed in a boiling hydrochloric acid bath to remove acid soluble materials.

After the acid bath, the sand sample was again washed. This time distilled water was used. It was found that three washes left the sand sufficiently clean for the next operation which was the addition of concentrated sodium hydroxide to a boiling suspension of the sample in distilled water. On the addition of sodium hydroxide a critical point was reached where the clay particles on the sand grains broke loose and the mixture took on a cloudy appearance. After the basic bath, the sand sample was washed in distilled water until a pH of 7 was obtained. The cleaned sand was then placed in an oven and dried.

A Lucite tube $3 \frac{3}{16}$ inches in diameter and 44 inches long was used to consolidate the sand by the use of silica solutions. For the consolidation of the sand, rubber stoppers were fitted in the Lucite tube with glass tubing inlets and fine mesh screen to keep the sand from passing out through

the tube, the stoppers were held in place by two $\frac{1}{4}$ inch steel tie rods.

To insure uniform consolidation of the core a wooden platform was constructed to support the Lucite tube. This platform with the Lucite tube was then placed on an electrical vibrator. During the operation of the vibrator, the entire assembly was rotated at specific intervals during the consolidation process. Next, Syton* was poured into the tube from the top until it filled the tube to a height of four or five inches. Sand was then allowed to flow into the tube in a slow steady stream, with additional Syton being added during the process to keep the fluid level four or five inches above the sand, in this manner, simultaneously filling the core with Syton and sand. The addition of sand and Syton was continued until the core was completely filled. Then hot dry air was passed through the core for one-hundred twenty hours to drive off all vapor present.

A vacuum pump was connected into the top and the core was completely evacuated. As a means of checking the dryness of the core, the vacuum pump was clamped off to see that the vacuum did not change, which would indicate the presence of vapor. With the core evacuated, alcohol was introduced into the bottom of the core until completely saturated and the alcohol was in turn displaced with tetraethyl orthosilicate by pressure.

The tetraethyl orthosilicate was then displaced and dried with hot dry air. The core was then again evacuated and saturated again with alcohol and tetraethyl orthosilicate, dried and then the process repeated again for the third time. The core was then considered consolidated enough for the experiment to be run.

After the consolidation was completed, four inches was cut off of each

*

Obtainable from the Monsanto Chemical Company, Boston, Massachusetts.

end of the core to eliminate any clogging of the ends during the consolidation process. Lucite end plates specially machined with Neoprene gaskets to seal the ends were fitted on the core being held in place by means of four steel tie rods. The core was then tapped at eleven inch intervals for both electrical and pressure connections to facilitate the taking of pressure drop and electrical potential readings along the core. Lucite fittings were machined for the Lucite end plates so that pressure taps, as well as inlet and outlet connections, could be taken off of each end. Lucite fittings were machined for the pressure taps along the core. Tygon* tubing was used in making connections from the core to the mercury manometers. Inlet and outlet connections were also made of Tygon tubing since it would stand a fairly high pressure; and was flexible and transparent which enabled the operator to observe any air or other undesirable substances in the lines.

In making the electrical taps, a hole was drilled in the Lucite tubing just into the core proper. Then this hole was filled with hot Woods metal, to insure good contact with the sand face, and again drilled to a given depth to allow for threads to be tapped so that the electrical tap, which was a brass screw with an electrical wire soldered to one end of it, could be tightened against the Woods metal contact. After screwing in the electrical tap, plastic tubing was used to insulate the outside of the tap and the electrical wiring from the water bath.

Two aspirator bottles with a capacity of two liters each were used as reservoirs to contain the fluid that was to be forced into the core. The bottom connection conducted the fluid to the core. A piece of glass tubing was extended down through the stopper in the bottles to admit the incoming air

* Obtainable from Central Scientific Supply Company, Oklahoma City, Oklahoma.

at a point near the bottom of the bottle. The outlet lines from the bottles were directed to a three way valve to facilitate the changing the fluid flow from one bottle to the other. Tygon tubing was used in making all connections since a pinch clamp could be used to stop off flow so that either bottle could be refilled without disturbing the operation of the other, thereby, allowing the test to be carried on without interruption.

Pressure from the laboratory air supply at 150 pounds per square inch was reduced to the desired pressure by a one stage pressure regulator.

Before entering the core, the displacing fluid was passed through approximately two and one-half feet of tubing submerged in the constant temperature bath to bring it up to temperature.

The end connection of Tygon tubing was cut to the desired length to allow it to extend over the constant temperature bath and down to the same level on the other side where the efflux from the core was caught in a graduated cylinder.

After the core was completed, porosity and permeability runs were made. The porosity was checked by two methods. The first method was to subject the core to pressure and recording the pressure then bleeding off a recorded volume of air and recording this new pressure. Then by use of the perfect gas law, the amount of void space was calculated.

The second method was to completely dry the core, to weigh it and then to saturate it completely with distilled water and again weighing. By taking the weight difference, the volume of water was calculated and the void space was again calculated. A close agreement was found between the two methods of obtaining the porosity value of 32.6 percent, which was used for this experiment.

A series of permeability tests were then made on the core and it was

found to be uniform, having a water permeability of 6 darcys.

The oils used in this experiment were Apco 476, Naptha, SAE 20 weight motor oil and mixtures of the above. Viscosities of the oils used were determined by means of an Ostwald viscosimeter and densities with the Westphal Balance.

The temperature of the water bath was maintained constant by heating it in a rectangular, metal lined, insulated tank with thermostatically controlled immersion heater.

The electrical potential across the core was provided by means of a twenty-four volt half wave rectifier which was stepped up to 375 volts by means of a dynamotor. Conductivity across the core was measured by means of three stepped ammeters with two selector switches which were used in selecting the electrodes and the ammeters. The pressure manometers were mounted on a panel board attached to the back of the constant temperature bath. An extra manometer for measuring the vacuum during the cleaning process was also mounted on the panel board.

Chapter V

Experimental Procedure

At the end of each run the core was flushed out with approximately two and one-half pore volumes of white gasoline to remove the heavier residual oil fractions, then the gasoline and remaining water was forced out with hot dry air and the core was allowed to dry for twenty-four hours.

At the end of twenty-four hours, the core was then evacuated and tested for dryness by clamping off the vacuum pump and seeing that the vacuum did not change. With the core completely evacuated and in a vertical position and the vacuum pump connected at the top, water was admitted at the bottom under approximately fifteen psi until the core was completely saturated. The vacuum pump was then shut off and two or three pore volumes of distilled water were allowed to pass through the core under pressure to clean out any residue that might be left in the core.

After the core was completely saturated with distilled water, this was in turn flooded out with the oil sample on which the test was to be run. The flooding out of the water by oil was continued until the water percentage in the efflux was one-half of a percent or less. When this point was reached the core was considered saturated and ready for the test.

The amount of water displaced from the core during the saturation with oil was carefully measured and recorded, since this was the exact amount of oil left in the core.

The constant temperature bath was brought up to a predetermined temperature and the core was submerged in the bath during the saturation with water and subsequent flooding with oil to insure temperature equilibrium between the core and bath.

After the core was saturated, the end connections were clamped and the reservoirs were filled with distilled water and brought up to the pressure to be used during the run.

In preparation for starting the test, the manometers were connected in by means of valves and the clamp on the inlet line was removed and the core brought up to pressure. After a check of the apparatus to see that everything was ready, the outlet clamp was removed and the displacement of the oil by the water was started. The efflux was caught in a graduate and recorded at specified time intervals.

The pressure and temperature were kept constant throughout a run. The amount of fluid, both oil and water was then plotted against total amount of efflux to eliminate pressure fluctuations in the analysis of the data since both are functions of pressure.

Viscosity measurements were made using a standard Ostwald viscosimeter and densities were obtained by means of a Westphal balance.

Time of efflux on the Ostwald and densities with the Westphal balance were taken at several temperatures between 80 and 130 degrees Fahrenheit. By using semi-log paper time of efflux versus temperature plot as a straight line and using coordinate paper densities versus temperature plot as a straight line.

Viscosities were obtained by using the equation:

$$\mu = (C_w t - \frac{\beta}{t}) \rho$$

where; C_w = Calibration constant determined with water.

β = Constant determined by design of instrument.

t = Time of efflux in seconds.

ρ = Density of fluid in grams per cubic centimeter.

μ = Viscosity in centipoises.

Viscosities from the above equation were plotted against the reciprocal of absolute temperature which gave a straight line plot on semi-log paper when viscosities are plotted on the log scale.

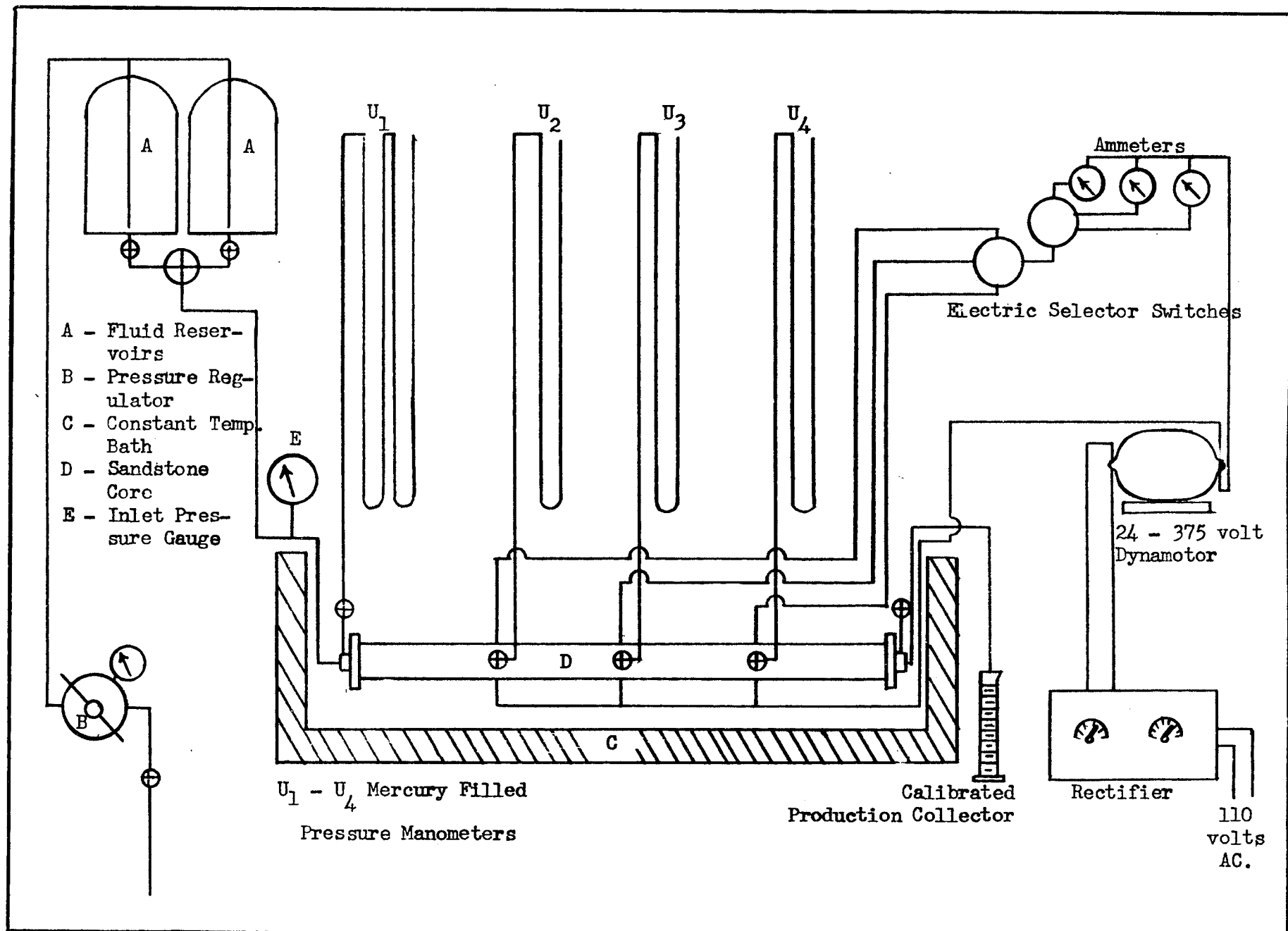


Fig. 1a. Sketch of Apparatus

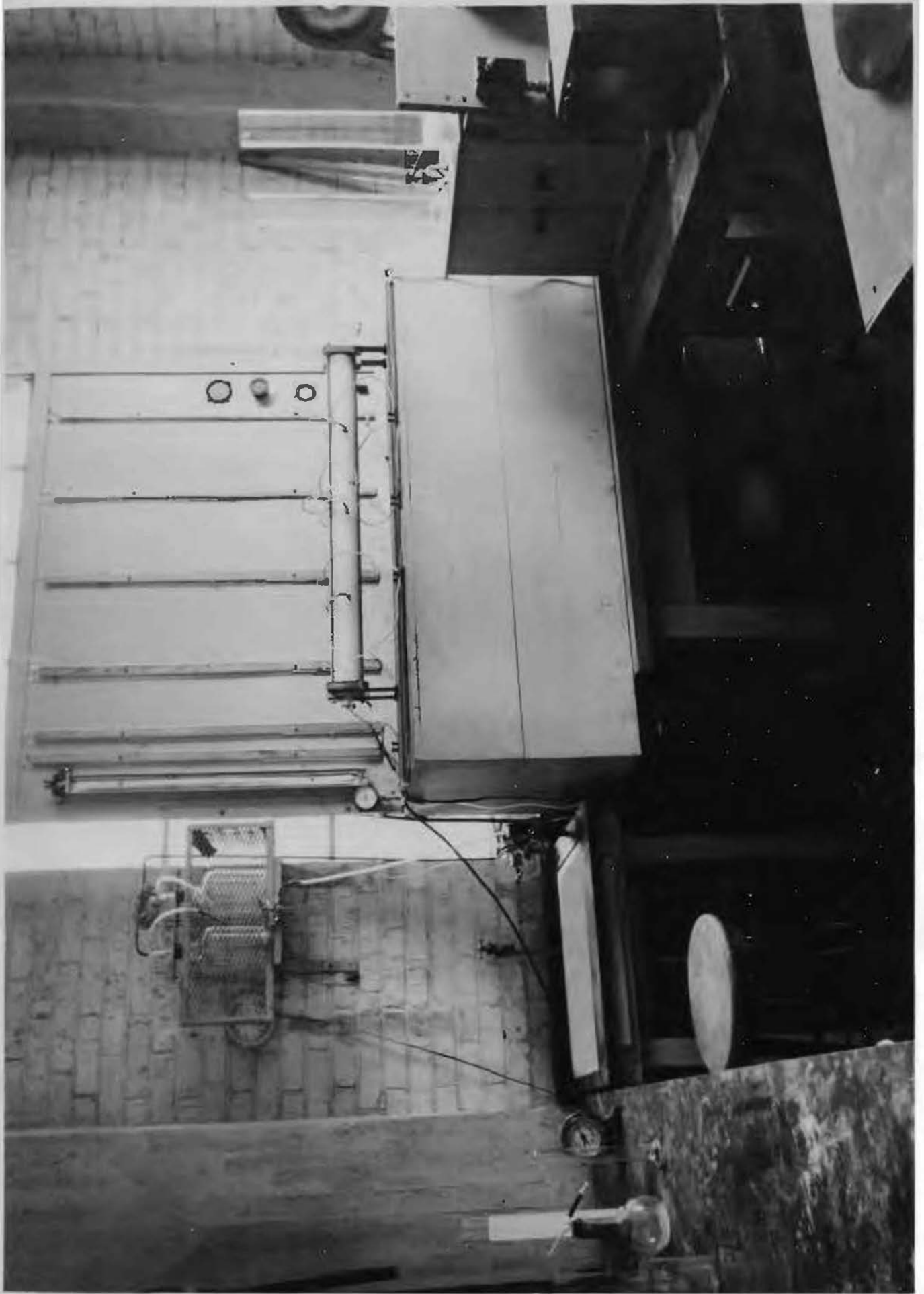


Fig. 1b. View of Experimental Equipment.



Fig. 1c. View of Viscosity Measuring Equipment and Vibrator.

TABLE I

Run Number 1

Temperature - 98°F
 Viscosity of oil - 2.6 cp
 Viscosity of water - 0.71 cp
 Date of run - May 5, 1951

Amount of oil in core - 1245 cc
 Type of oil in core - Blend Number 1
 Displacing fluid - Distilled water
 Pressure - 15 psi

Time (min)	vt	Vt	vo	Vo	vw	Vw	vo/vw	Q
2	98.0	98.0	97.0	97.0	1.0	1.0	99.00	0.058
4	93.0	191.0	91.0	188.0	2.0	3.0	98.00	0.112
6	89.0	280.0	81.0	269.0	8.0	11.0	91.00	0.165
8	91.5	371.5	70.5	339.5	21.0	32.0	77.00	0.218
10	91.0	462.5	62.0	401.5	29.0	61.0	68.20	0.272
12	103.0	565.5	59.0	460.5	44.0	105.0	57.30	0.333
14	107.0	672.5	53.0	513.5	54.0	159.0	48.60	0.396
16	111.0	783.5	47.0	560.5	64.0	223.0	42.30	0.461
18	116.0	899.5	42.0	602.5	74.0	297.0	36.20	0.528
20	120.0	1019.5	38.5	641.0	81.5	378.5	32.00	0.600
22	124.0	1143.5	29.0	670.0	95.0	473.5	23.40	0.674
24	130.0	1273.5	26.0	696.0	104.0	577.5	20.00	0.750
26	137.0	1410.5	20.0	716.0	117.0	694.5	14.60	0.830
28	139.0	1549.5	19.0	735.0	120.0	814.5	13.70	0.910
30	145.0	1694.5	17.0	752.0	128.0	942.5	11.70	1.000
32	146.0	1840.5	14.0	766.0	132.0	1074.5	9.60	1.080
34	146.0	1986.5	10.0	776.0	136.0	1210.5	6.85	1.170
36	146.0	2132.5	8.0	784.0	138.0	1348.5	5.48	1.250
38	146.0	2278.5	6.0	790.0	140.0	1488.5	4.10	1.340
40	147.0	2425.5	5.0	795.0	142.0	1630.5	3.40	1.430
44	290.8	2716.3	7.8	802.8	283.0	1913.5	2.68	1.600
48	287.2	3003.5	6.0	808.8	281.2	2194.7	2.09	1.770
52	300.5	3304.0	5.3	814.1	295.2	2489.9	1.77	1.950
56	300.2	3604.2	3.7	817.8	296.5	2786.4	1.23	2.120
60	295.0	3899.2	4.0	821.8	291.0	3077.4	1.35	2.290
64	283.5	4182.7	2.5	824.3	281.0	3358.4	0.88	2.470

TABLE II

Run Number 2

Temperature - 90°F
 Viscosity of oil - 3.85 cp
 Viscosity of water - 0.79 cp
 Date of run - May 7, 1951

Amount of oil in core - 1245 cc
 Type of oil in core - Blend number 2
 Displacing fluid - Distilled water
 Pressure - 15 psi

Time (min)	vt	Vt	vo	Vo	vw	Vw	vo/vw	Q
2	61.0	61.0	61.0	61.0	0.0	0.0	100.00	.036
4	67.0	128.0	66.0	127.0	1.0	1.0	98.50	.075
6	71.0	199.0	66.0	193.0	5.0	6.0	93.00	.117
8	74.0	273.0	57.0	250.0	17.0	23.0	77.00	.160
10	83.0	356.0	52.0	302.0	31.0	54.0	62.60	.210
12	88.0	444.0	46.0	348.0	42.0	96.0	52.30	.261
14	93.0	537.0	42.0	390.0	51.0	147.0	45.20	.315
16	99.0	636.0	41.0	431.0	58.0	205.0	41.40	.374
18	106.0	742.0	40.0	471.0	66.0	271.0	37.80	.436
20	111.0	853.0	32.0	503.0	79.0	350.0	28.80	.500
22	106.0	959.0	20.0	523.0	86.0	436.0	18.90	.564
24	119.0	1078.0	28.0	551.0	91.0	527.0	23.50	.634
26	228.0	1206.0	25.0	576.0	103.0	630.0	11.00	.710
28	131.0	1337.0	21.0	597.0	110.0	740.0	16.00	.787
30	131.0	1468.0	18.0	615.0	113.0	853.0	13.70	.864
32	133.0	1601.0	16.0	631.0	117.0	970.0	12.00	.945
34	140.0	1741.0	20.0	651.0	120.0	1090.0	14.25	1.025
36	144.0	1885.0	18.0	669.0	126.0	1216.0	12.50	1.110
38	141.0	2026.0	10.0	679.0	131.0	1347.0	7.10	1.190
40	140.0	2166.0	8.0	687.0	132.0	1479.0	5.70	1.270
44	296.0	2462.0	18.0	705.0	278.0	1757.0	6.10	1.450
48	317.0	2779.0	23.0	728.0	294.0	2051.0	7.26	1.635
52	309.0	3088.0	13.0	741.0	296.0	2347.0	4.20	1.815
56	307.5	3395.5	10.5	751.5	297.0	2644.0	3.41	2.000
60	320.0	3715.5	8.5	760.0	311.5	2955.5	2.65	2.180
64	314.0	4029.5	6.0	766.0	308.0	3263.5	1.91	2.370
66	178.0	4207.5	2.0	768.0	176.0	3439.5	1.12	2.470
75	1095.0	5302.5	15.0	783.0	1080.0	4519.5	1.37	3.120
85	717.0	6020.0	22.0	805.0	695.5	5215.0	3.07	3.540

TABLE III

Run Number 3

Temperature - 90°F
 Viscosity of oil - 1.6 cp
 Viscosity of water - 0.79 cp
 Date of run - May 10, 1951

Amount of oil in core - 1272.5 cc
 Type of oil in core - APCO 467
 Displacing fluid - Distilled water
 Pressure - 15 psi

Time (min)	vt	Vt	vo	Vo	vw	Vw	vo/vw	Q
2	229.0	229.0	225.0	225.0	4.0	4.0	98.50	0.135
4	214.0	443.0	179.0	404.0	35.5	39.5	83.70	0.260
6	215.0	658.0	134.0	538.0	80.5	120.0	62.30	0.388
8	226.0	884.0	98.0	636.0	128.0	248.0	43.30	0.520
10	228.0	1112.0	80.0	716.0	148.0	396.0	35.0	0.654
12	235.0	1347.0	60.0	776.0	175.0	571.0	25.50	0.794
14	235.0	1582.0	30.0	806.0	205.0	776.0	12.80	0.932
16	242.0	1824.0	17.0	823.0	225.0	1001.0	7.02	1.075
18	242.0	2066.0	16.0	839.0	226.0	1227.0	6.62	1.220
20	240.0	2306.0	14.0	853.0	226.0	1452.0	5.83	1.360
22	243.0	2549.0	8.0	861.0	235.0	1687.0	3.29	1.500
24	241.0	2790.0	4.0	865.0	237.0	1925.0	1.66	1.640
26	250.0	3040.0	3.0	868.0	247.0	2172.0	1.20	1.790
28	247.0	3287.0	3.0	871.0	244.0	2416.0	1.21	1.940
30	247.0	3534.0	3.0	874.0	244.0	2660.0	1.21	2.080
31.5	175.0	3707.0	2.0	876.0	173.0	2833.0	1.14	2.180
34	357.0	4066.0	1.0	877.0	356.0	3189.0	0.28	2.400
36	252.3	4318.3	2.8	879.8	249.5	3438.5	1.10	2.540

TABLE IV

Run Number 4

Temperature - 90°F
 Viscosity of oil - 0.83 cp
 Viscosity of water - 0.79 cp
 Date of run - May 19, 1951

Amount of oil in core - 1200 cc
 Type of oil in core - Naphtha
 Displacing fluid - Distilled water
 Pressure - 5 psi

Time (min)	vt	Vt	vo	Vo	vw	Vw	vo/vw	Q
2	105	105	105	105	0	0	100.00	0.062
4	88	193	88	193	0	0	100.00	0.114
6	100	293	100	293	0	0	100.00	0.173
8	97	390	97	390	0	0	100.00	0.230
10	102	492	100	490	2	2	98.00	0.290
12	95	587	87	577	8	10	91.50	0.345
14	85	672	62	639	23	33	73.00	0.397
16	85	757	53	692	32	65	62.40	0.445
18	79	836	37	729	42	107	46.80	0.492
20	70	906	20	749	50	157	28.60	0.533
22	77	983	15	764	62	219	19.50	0.578
24	82	1065	13	777	69	288	15.85	0.627
26	82	1147	10	787	72	360	12.20	0.675
28	83	1230	9	796	74	434	10.85	0.725
30	88	1318	9	805	79	513	10.20	0.775
34	185	1503	14	819	171	684	7.57	0.885
39	223	1726	15	834	208	892	6.74	1.015
46	255	1981	13	847	242	1134	5.10	1.170
50	281	2262	9	856	272	1406	3.20	1.330
56	290	2552	9	865	281	1687	3.10	1.500
60	205	2757	8	873	197	1884	3.90	1.620
65	212	2969	6	879	206	2090	2.83	1.750
70	245	3214	5	884	240	2330	2.04	1.890
75	240	3454	4	888	236	2566	1.67	2.030
80	232	3686	4	892	228	2794	1.72	2.170
90	468	4154	4	896	464	3258	0.86	2.450
100	462	4616	2	898	460	3718	0.43	2.720
110	461	5077	2	900	459	4177	0.43	2.980
	405	5482	1	901	404	4581	0.25	3.230

TABLE V

Run Number 5

Temperature - 90°F
 Viscosity of oil - 5.92
 Viscosity of water - 0.79 cc
 Date of run - May 22, 1951

Amount of oil in core - 1388 cc
 Type of oil in core - Blend number 4
 Displacing fluid - Distilled water
 Pressure - 5 psi

Time (min)	vt	Vt	vo	Vo	vw	Vw	vo/vw	Q
5	33.8	33.8	33.8	33.8	0	0	100.00	0.020
10	38.8	72.6	38.8	72.6	0	0	100.00	0.043
15	44.0	116.6	44.0	116.6	0	0	100.00	0.069
20	46.5	163.1	46.5	163.1	0	0	100.00	0.096
25	49.0	212.1	49.0	212.1	0	0	100.00	0.120
30	50.2	262.3	46.2	258.3	4	4	92.00	0.154
35	54.0	316.3	35.5	293.8	18.5	22.5	65.70	0.187
40	57.0	373.3	32.0	325.8	25.0	47.5	56.20	0.220
45	59.0	432.3	28.5	354.3	30.5	78.0	48.30	0.255
50	62.0	494.3	26.0	380.3	36.0	114.0	42.0	0.290
55	69.0	563.3	24.0	404.3	45.0	159.0	34.80	0.330
60	76.0	639.3	23.0	427.3	53.0	212.0	30.30	0.376
65	81.0	720.3	21.0	448.3	60.0	272.0	26.00	0.424
70	84.0	804.3	19.0	467.3	65.0	337.0	22.60	0.473
75	86.0	890.3	16.0	483.3	70.0	407.0	18.60	0.524
80	90.0	980.3	17.0	500.3	73.0	480.0	18.90	0.577
85	95.0	1075.3	15.0	515.3	80.0	560.0	15.80	0.634
90	100.0	1175.3	16.0	531.3	84.0	644.0	16.00	0.692
95	104.0	1279.3	15.0	546.3	89.0	733.0	14.40	0.750
105	220.0	1499.3	25.0	571.3	195.0	928.0	11.70	0.882
115	260.0	1759.3	23.0	594.3	237.0	1165.0	8.85	1.030
125	283.0	2042.3	23.0	617.3	260.0	1425.0	8.13	1.200
155	790.0	2832.3	65.0	682.3	725.0	2150.0	8.23	1.670
185	860.0	3691.3	52.0	734.3	808.0	2958.0	6.05	2.170
215	940.0	4632.3	30.0	764.3	910.0	3868.0	3.20	2.730
245	965.0	5597.3	25.0	789.3	940.0	4808.0	2.60	3.300
275	1075.0	6672.3	25.0	814.3	1050.0	5858.0	2.33	3.930
305	1120.0	7792.3	25.0	839.3	1095.0	6953.0	2.23	4.570
325	775.0	8567.4	5.0	844.3	770.0	7723.0	0.65	5.100
335	1132.0	9699.3	2.0	846.3	1130.0	8853.0	0.18	5.700
365	1192.0	10891.3	12.0	858.3	1180.0	10033.0	1.00	6.400
395	1290.0	12181.3	10.0	868.3	1280.0	11313.0	0.78	7.160
425	1277.0	13458.3	7.0	875.3	1270.0	12583.0	0.55	7.930

TABLE VI

Run Number 6

Temperature - 90°F
 Viscosity of oil - 11.48
 Viscosity of water - 0.79 cp
 Date of run - May 24, 1951

Amount of oil in core - 1319
 Type of oil in core - Blend Number 3
 Displacing fluid - Distilled water
 Pressure - 5 psi

Time (min)	vt	Vt	vo	Vo	vw	Vw	vo/vw	Q
10	73.0	73.0	73.5	73.0	0	0	100.00	0.043
20	82.0	155.0	82.0	155.0	0	0	100.00	0.091
30	75.0	230.0	75.0	230.0	0	0	100.00	0.135
40	82.0	312.0	82.0	312.0	0	0	100.00	0.184
50	90.0	402.0	90.0	402.0	0	0	100.00	0.236
55	52.0	454.0	46.5	448.2	5.5	5.5	89.50	0.267
60	55.0	509.0	30.0	478.5	25.0	30.5	54.50	0.300
65	56.0	565.0	25.0	503.5	31.0	61.5	44.70	0.332
70	61.0	626.0	22.0	525.5	39.0	100.5	36.00	0.368
75	66.0	672.0	23.0	548.5	43.0	143.0	35.00	0.395
80	66.5	758.5	16.5	565.0	50.0	193.0	24.80	0.446
85	71.0	829.5	16.0	581.0	55.0	248.0	22.60	0.487
90	77.0	906.5	15.0	596.0	62.0	310.0	19.50	0.533
95	72.0	978.5	12.0	608.0	60.0	370.0	16.70	0.575
100	74.0	1052.5	11.0	619.0	63.0	433.0	14.90	0.620
105	79.0	1131.5	11.0	630.0	68.0	501.0	14.0	0.667
110	84.0	1215.5	9.0	639.0	75.0	576.0	10.70	0.717
115	87.0	1302.5	9.5	648.5	77.5	654.0	10.90	0.766
120	90.0	1392.5	10.0	658.5	80.0	734.0	11.10	0.820
125	90.0	1482.5	9.0	667.5	81.0	815.0	10.00	0.874
130	90.0	1572.5	8.0	675.5	82.0	897.0	8.90	0.925
150	374.0	1946.5	27.0	702.5	347.0	1244.0	7.22	1.150
170	420.0	2366.5	25.0	727.5	395.0	1639.0	5.95	1.390
190	432.0	2798.5	25.0	752.5	407.0	2046.0	5.80	1.650
210	470.0	3268.5	22.0	774.5	448.0	2494.0	4.70	1.930
230	497.0	3765.5	20.0	794.5	477.0	2971.0	4.00	2.220
250	512.0	4277.5	17.0	811.5	495.0	3466.0	3.32	2.520
270	548.0	4825.5	14.5	826.0	533.5	3999.5	2.64	2.840
290	543.0	5368.5	11.0	837.0	532.0	4531.5	2.00	3.160
310	557.0	5925.5	10.0	847.0	547.0	5078.5	1.80	3.480
330	548.0	6473.5	9.0	856.0	539.0	5617.5	1.64	3.800

TABLE VII
Composite Data

Viscosity Ratio Oil/Water	Percent Oil Produced During the Initial Phase	Total Pore Volumes Through	Percent Oil Recovered
1.050	62.5	3.23	75.0
2.025	47.0	2.54	69.5
3.670	36.1	2.47	66.2
4.820	34.5	3.54	64.7
7.500	34.0	3.80	64.3
14.530	30.3	7.93	63.7

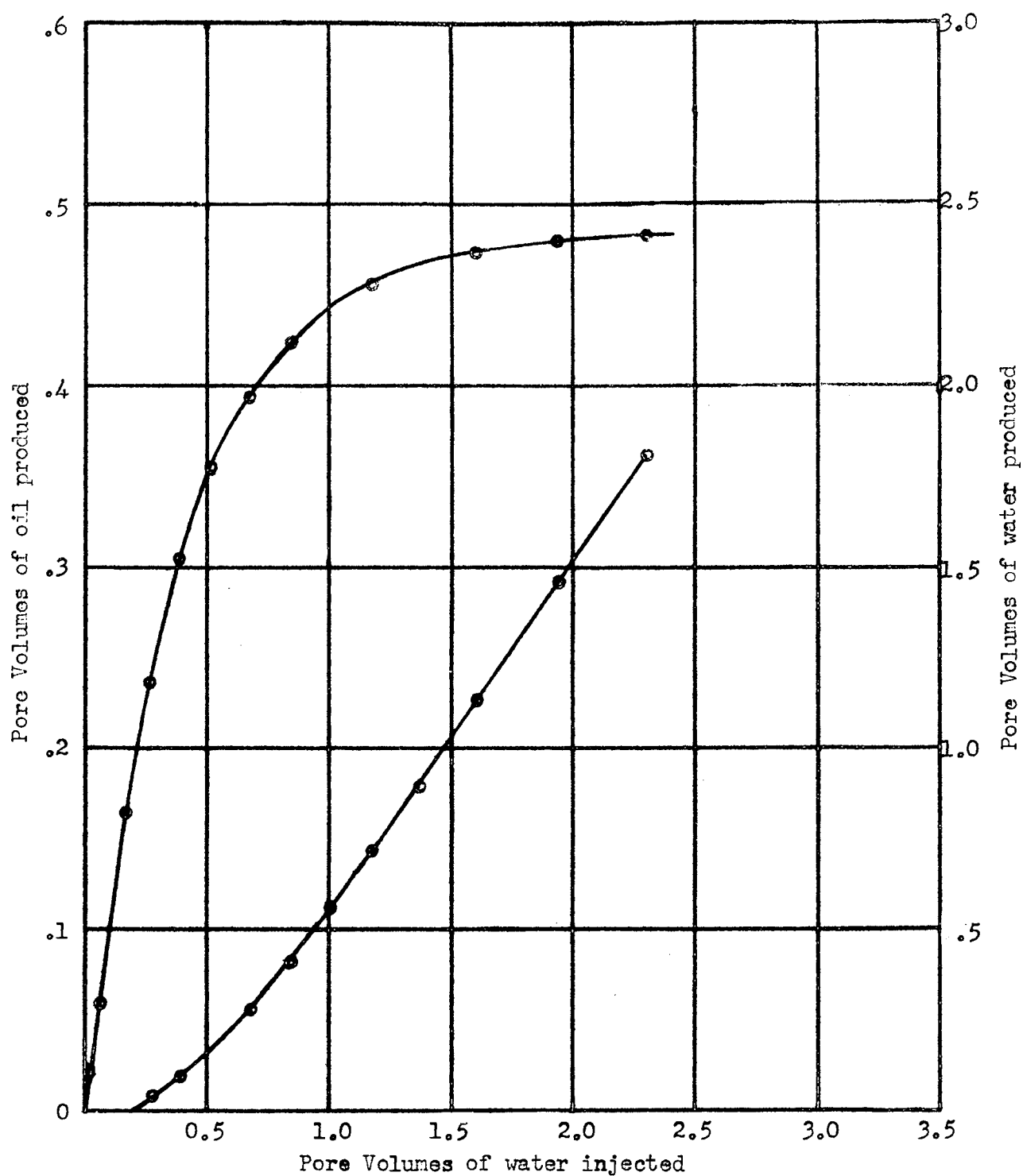


Fig. No. 1, Run No. 1
Oil and water produced versus water injected
Blend No. 1, Viscosity ratio oil/water 3.66

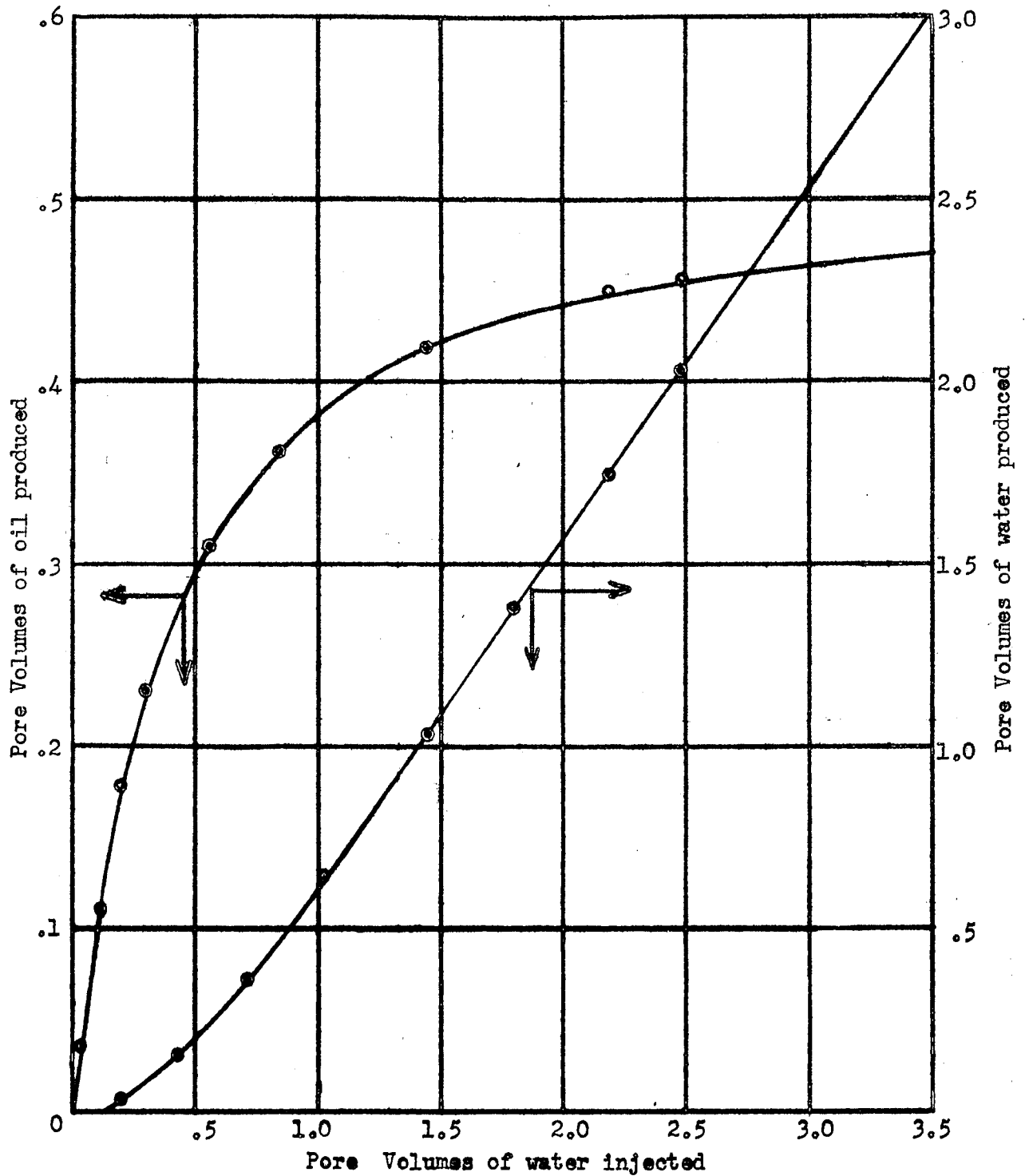


Fig. No. 2, Run No. 2
 Oil and water produced versus water injected
 Blend No. 2, Viscosity ratio oil/water 4.87

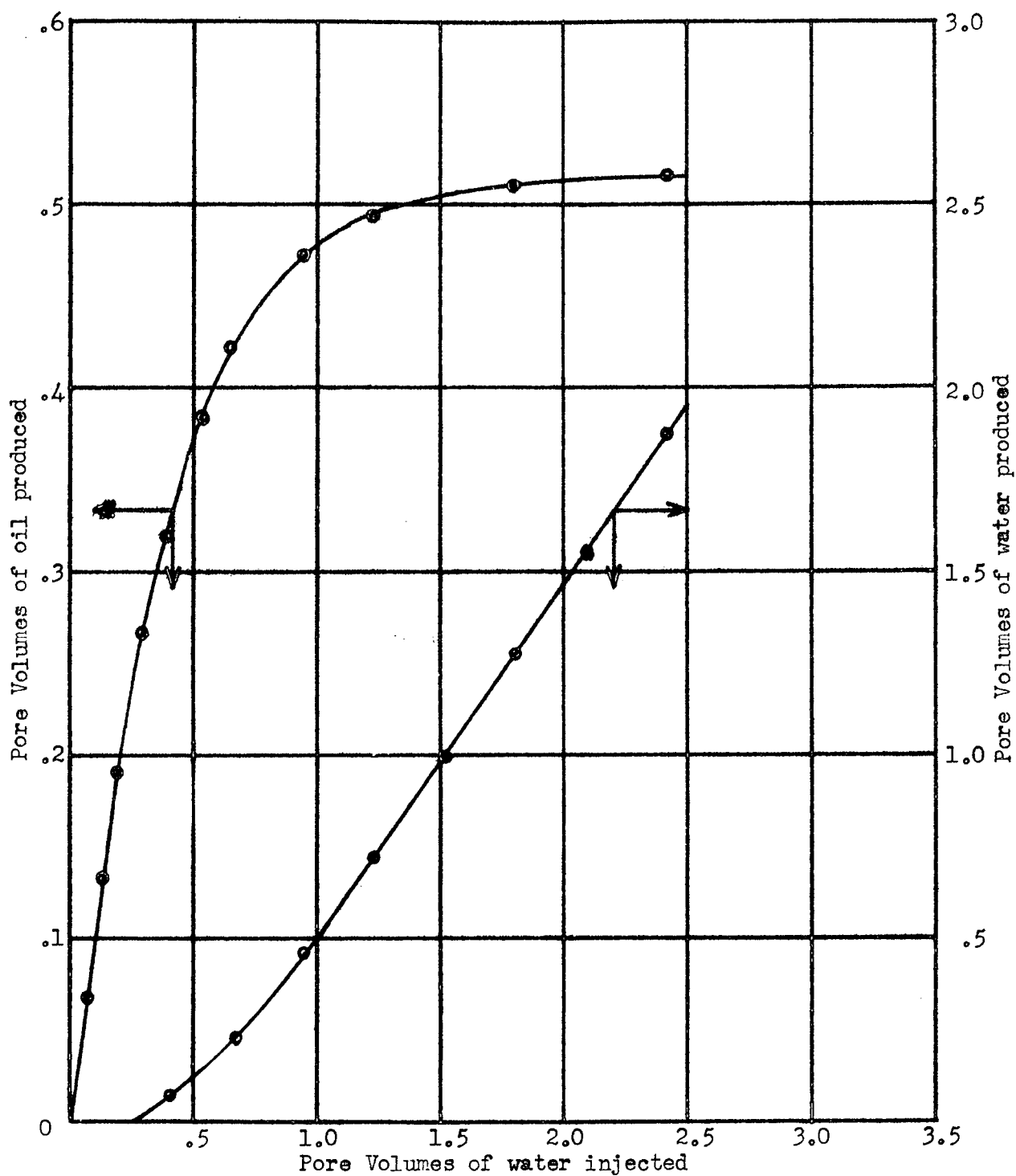


Fig. No. 3, Run No. 3
 Oil and water produced versus water injected
 APCO 467, Viscosity ration oil/water 2.025

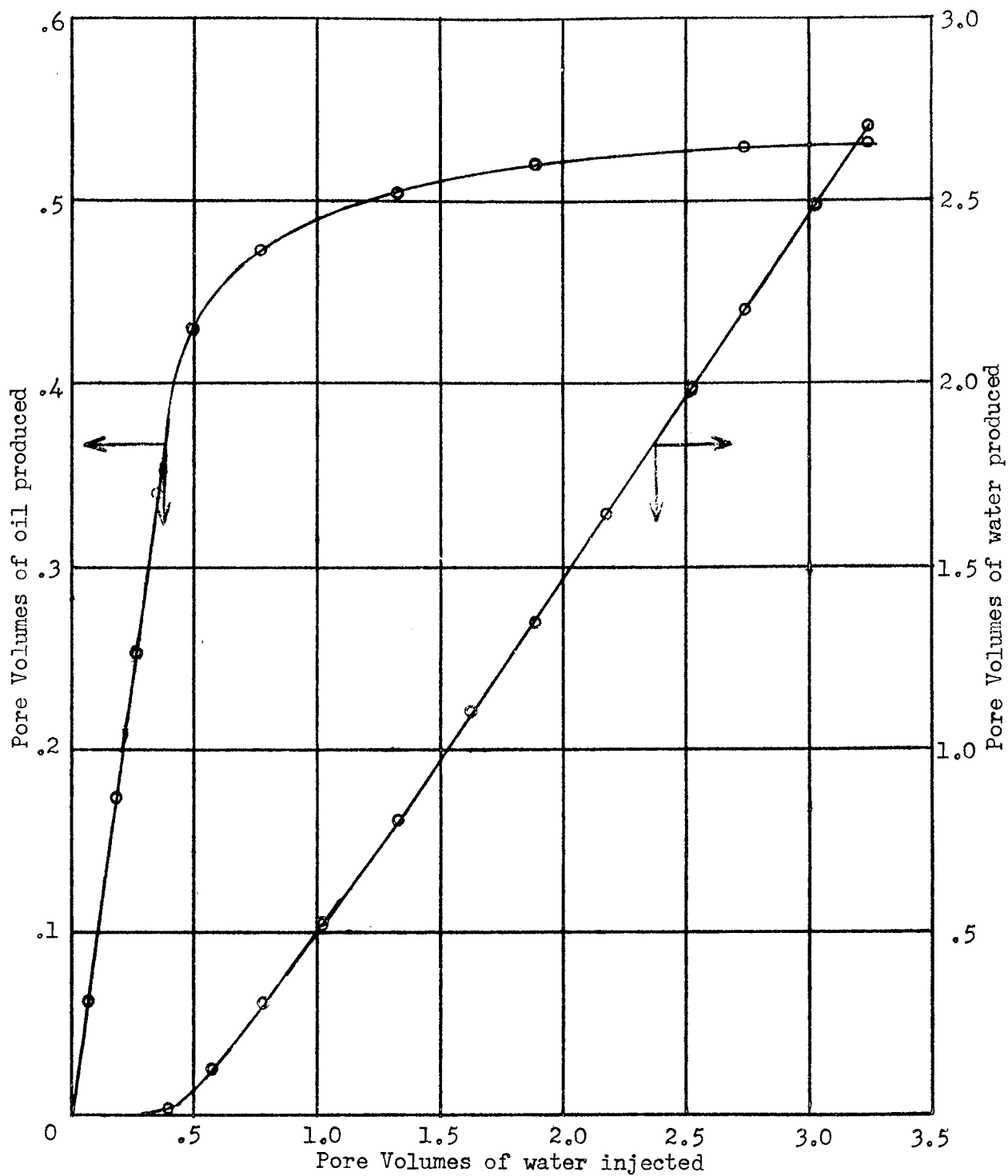


Fig. No. 4, Run No. 4

Oil and water produced versus water injected
 Naphtha, Viscosity ratio oil/water 1.05

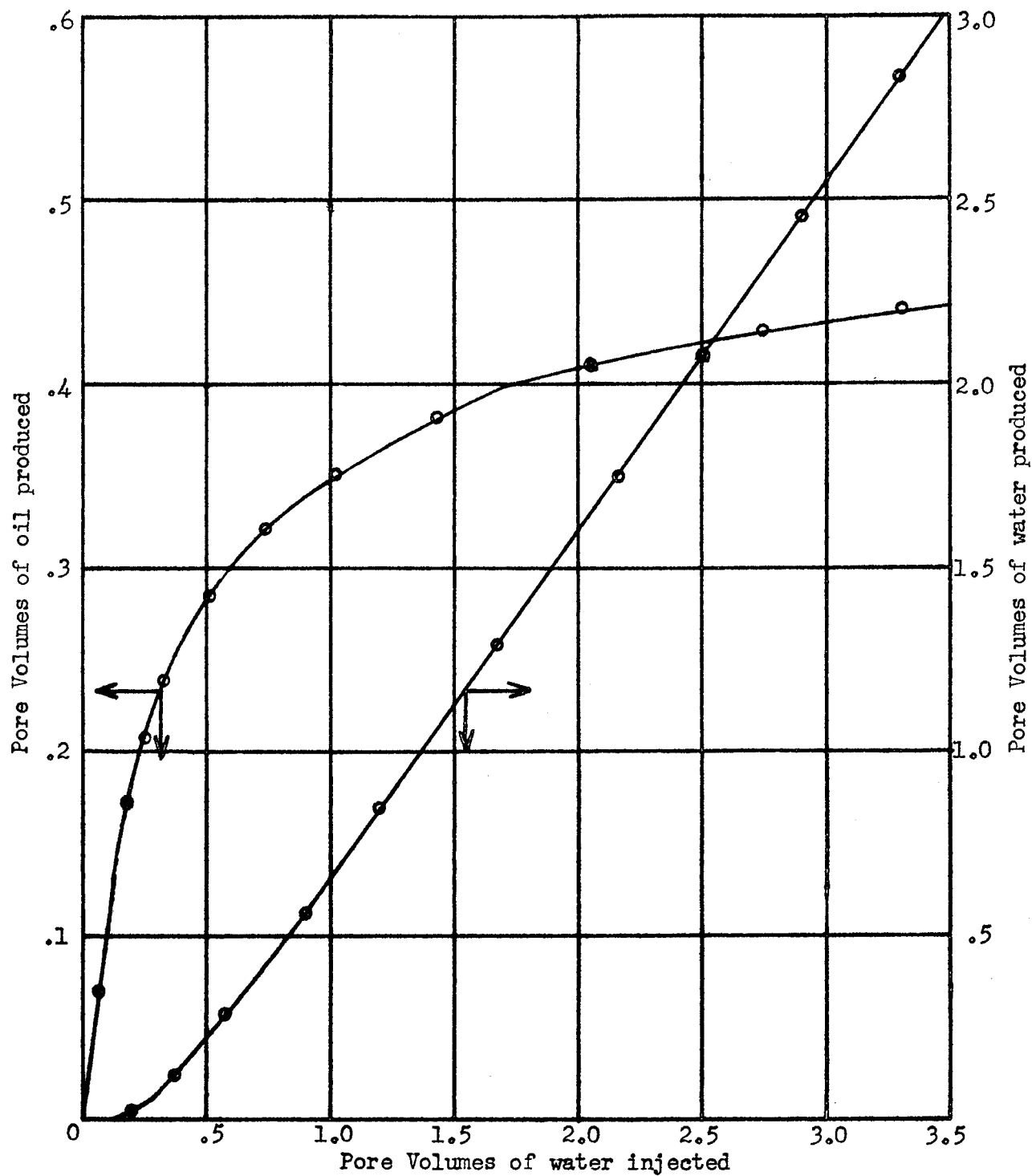


Fig. No. 5, Run No. 5
 Oil and water produced versus water injected
 Blend No. 4, Viscosity ratio oil/water 14.53

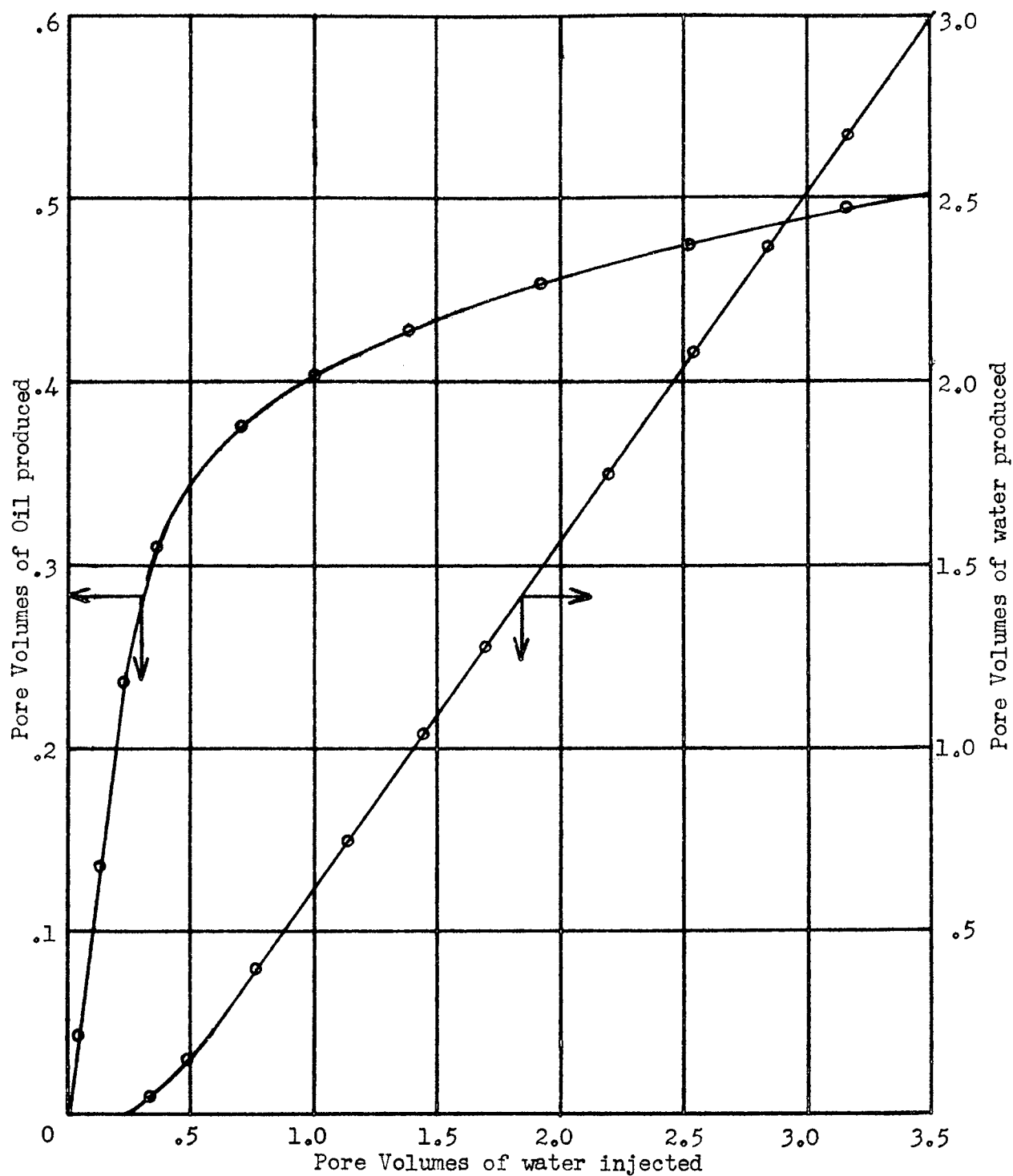


Fig. No. 6, Run No. 6
 Oil and water produced versus water injected
 Blend No. 3, Viscosity ratio oil/water 7.5

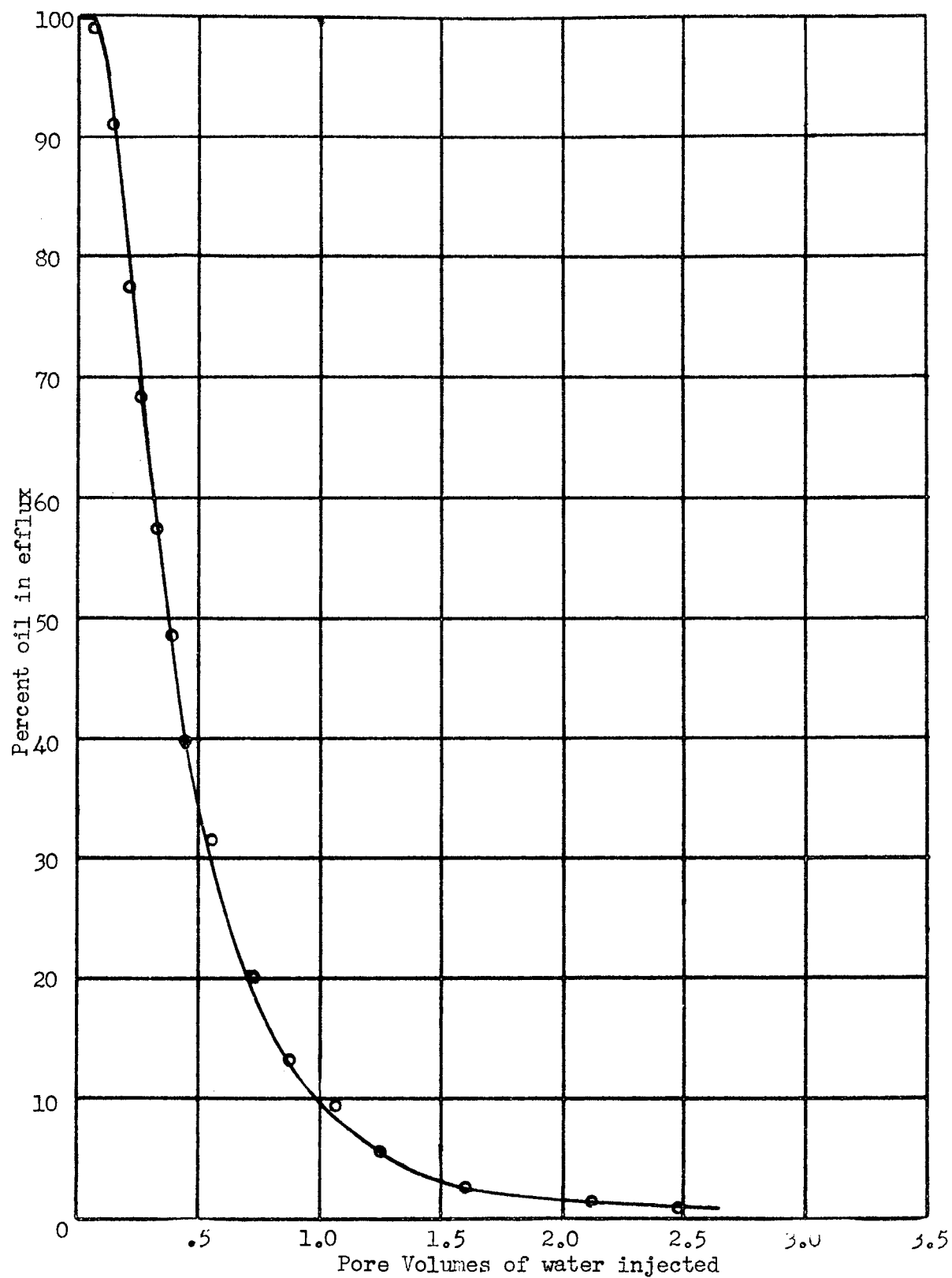


Fig. No. 7, Run No. 7
Percent oil in efflux versus Pore Volumes of water injected
Blend No. 1, Viscosity ratio oil/water 3.66

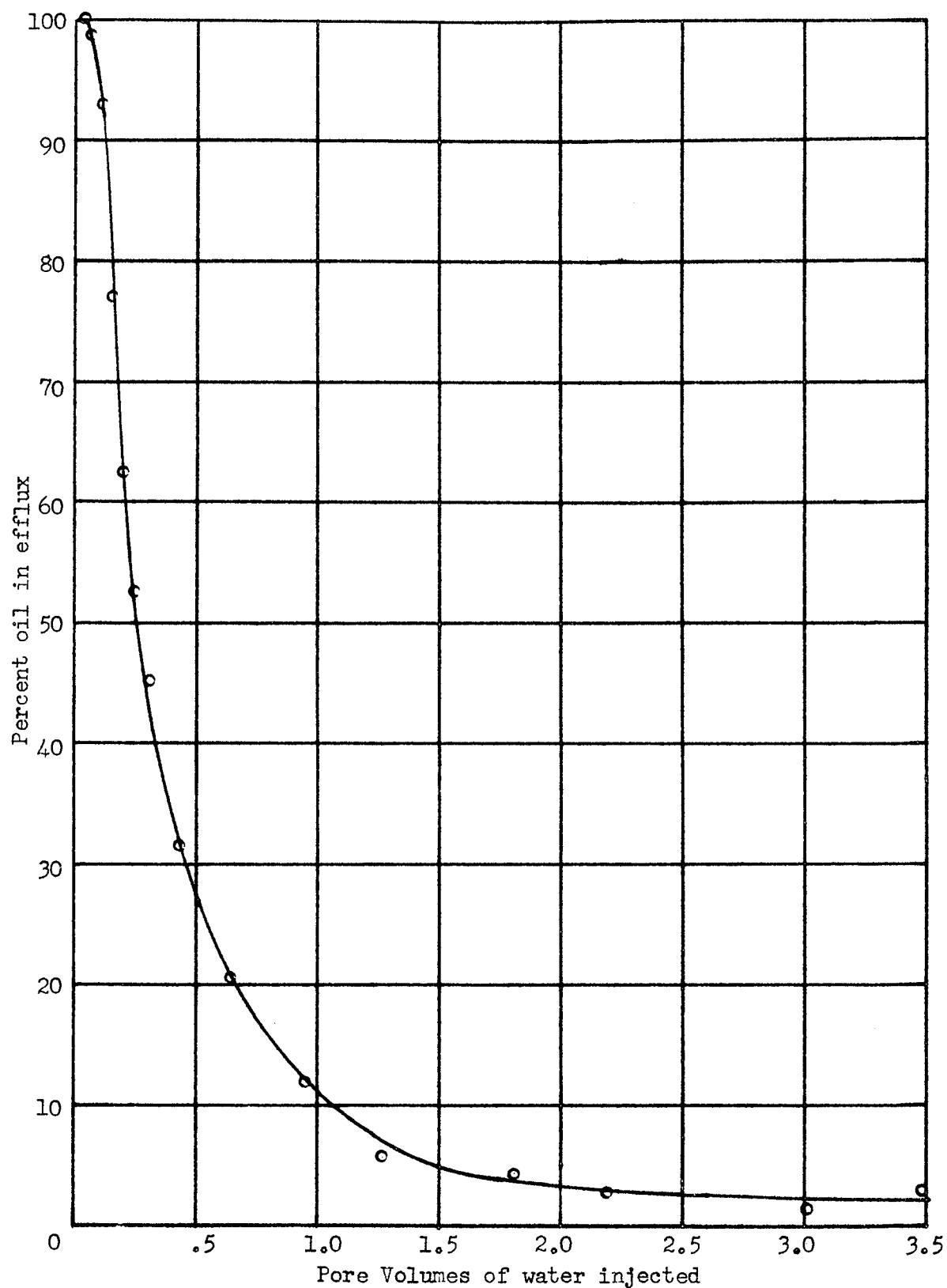


Fig. No. 8, Run No. 2
Percent oil in efflux versus Pore Volumes of water injected
Blend No. 2, Viscosity ratio oil/water 4.87

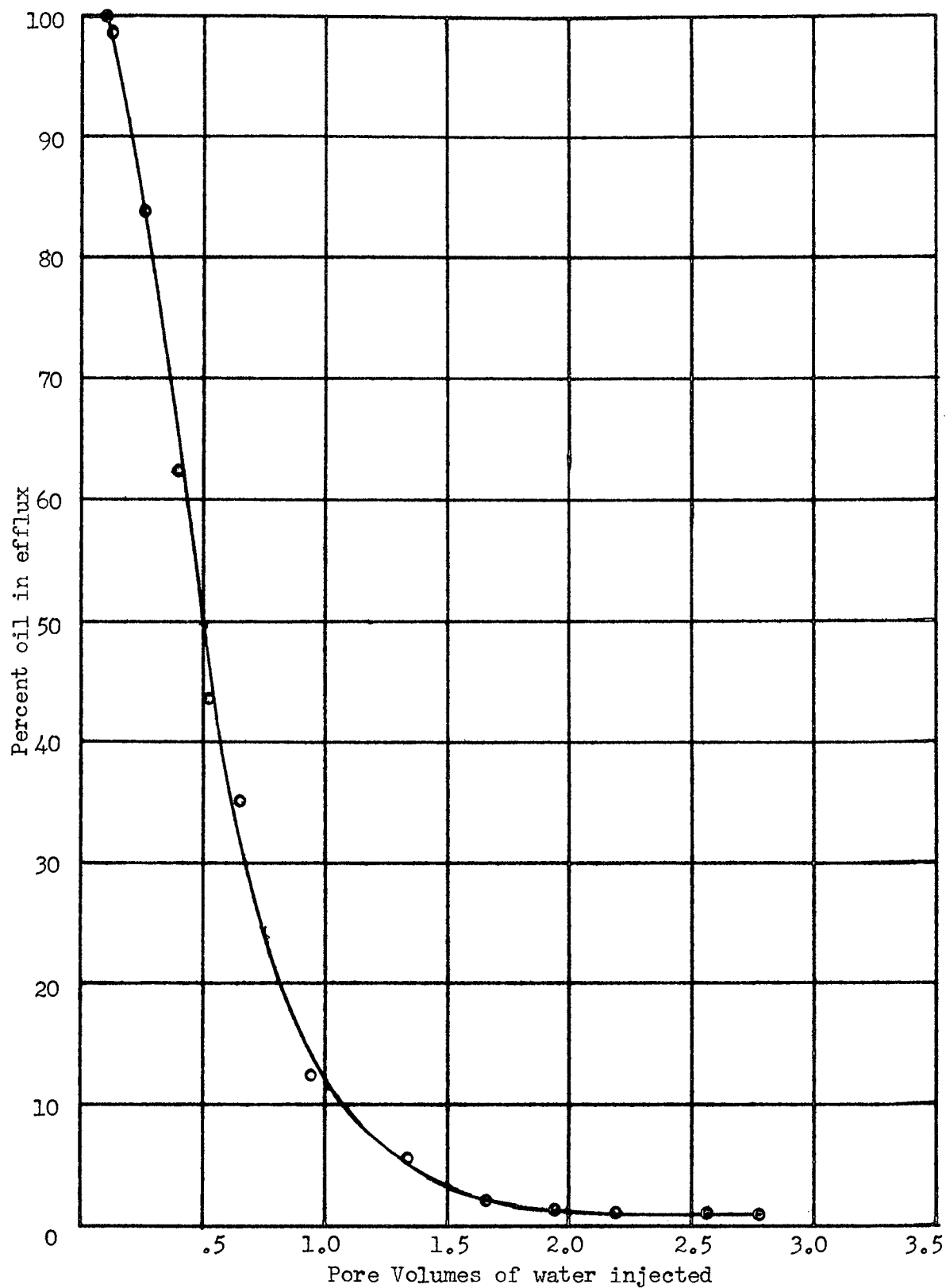


Fig. No. 9, Run No. 3
Percent oil in efflux versus Pore Volumes of water injected
APCO 476, Viscosity ratio oil/water 2.025

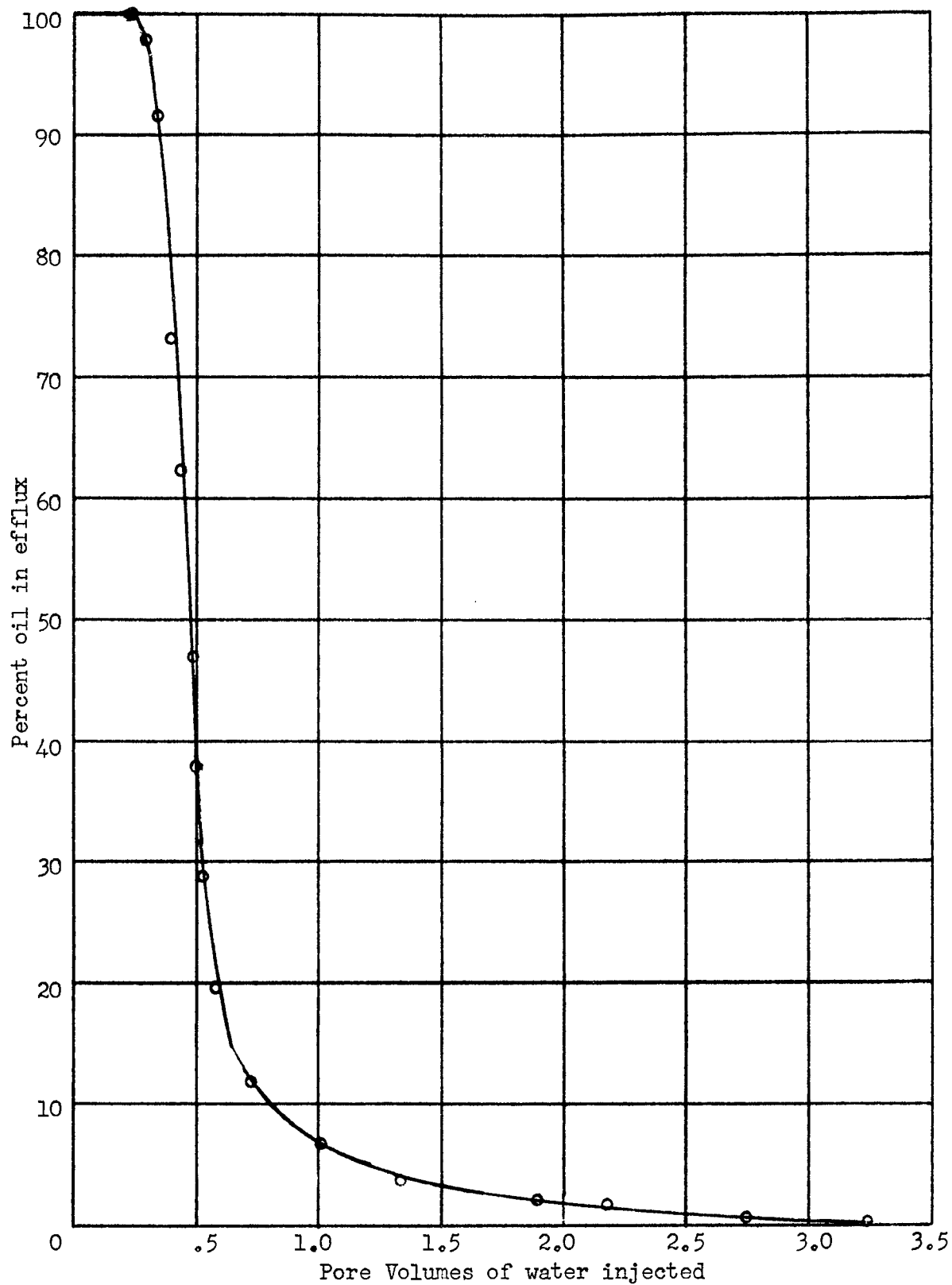


Fig. No. 10, Run No. 4
Percent oil in efflux versus Pore Volumes of water injected
Naptha, Viscosity ratio oil/water 1.05

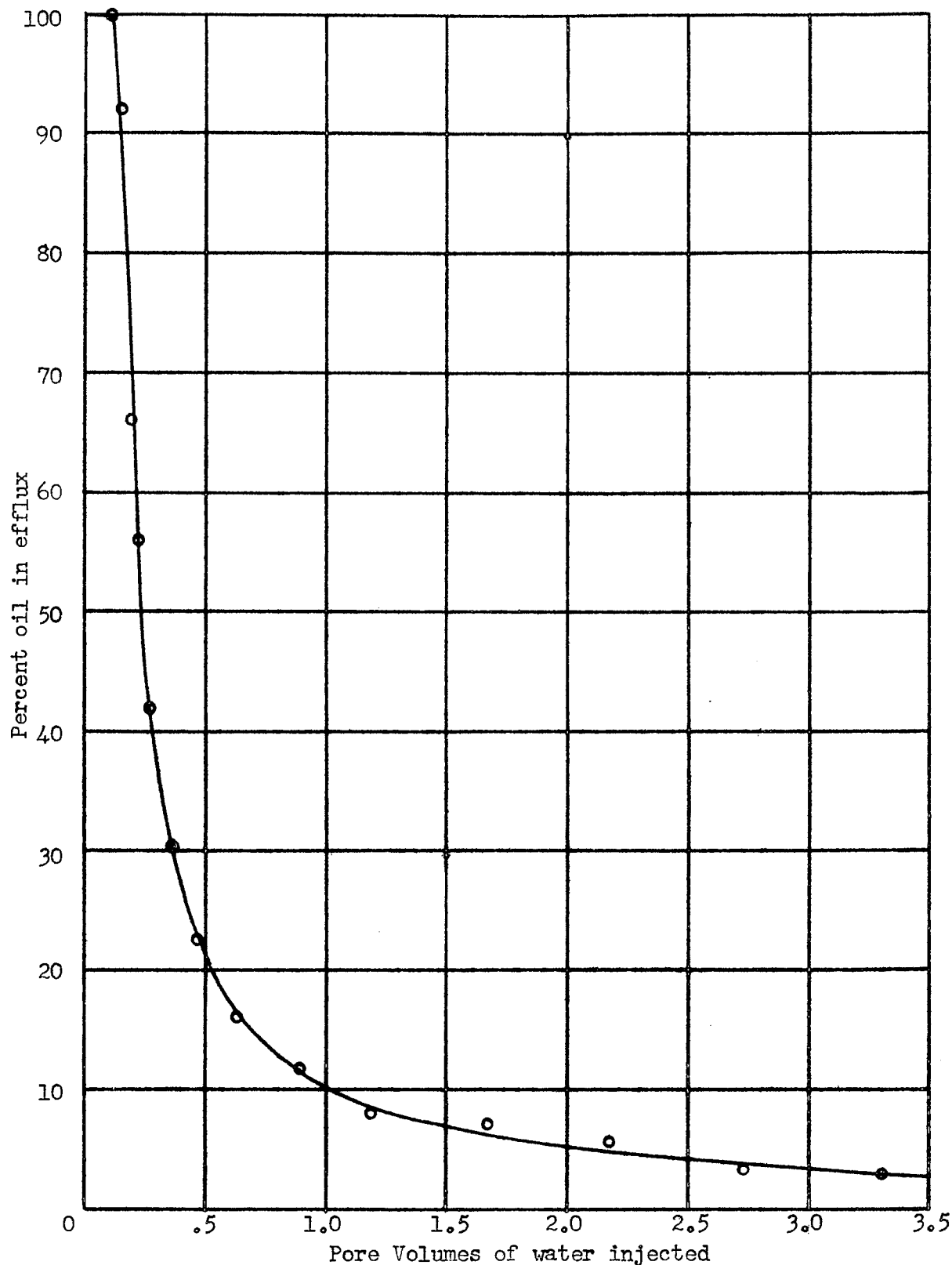


Fig. No. 11, Run No. 5
Percent oil in efflux versus Pore Volumes of water injected
Blend No. 4, Viscosity ratio oil/water 14.53

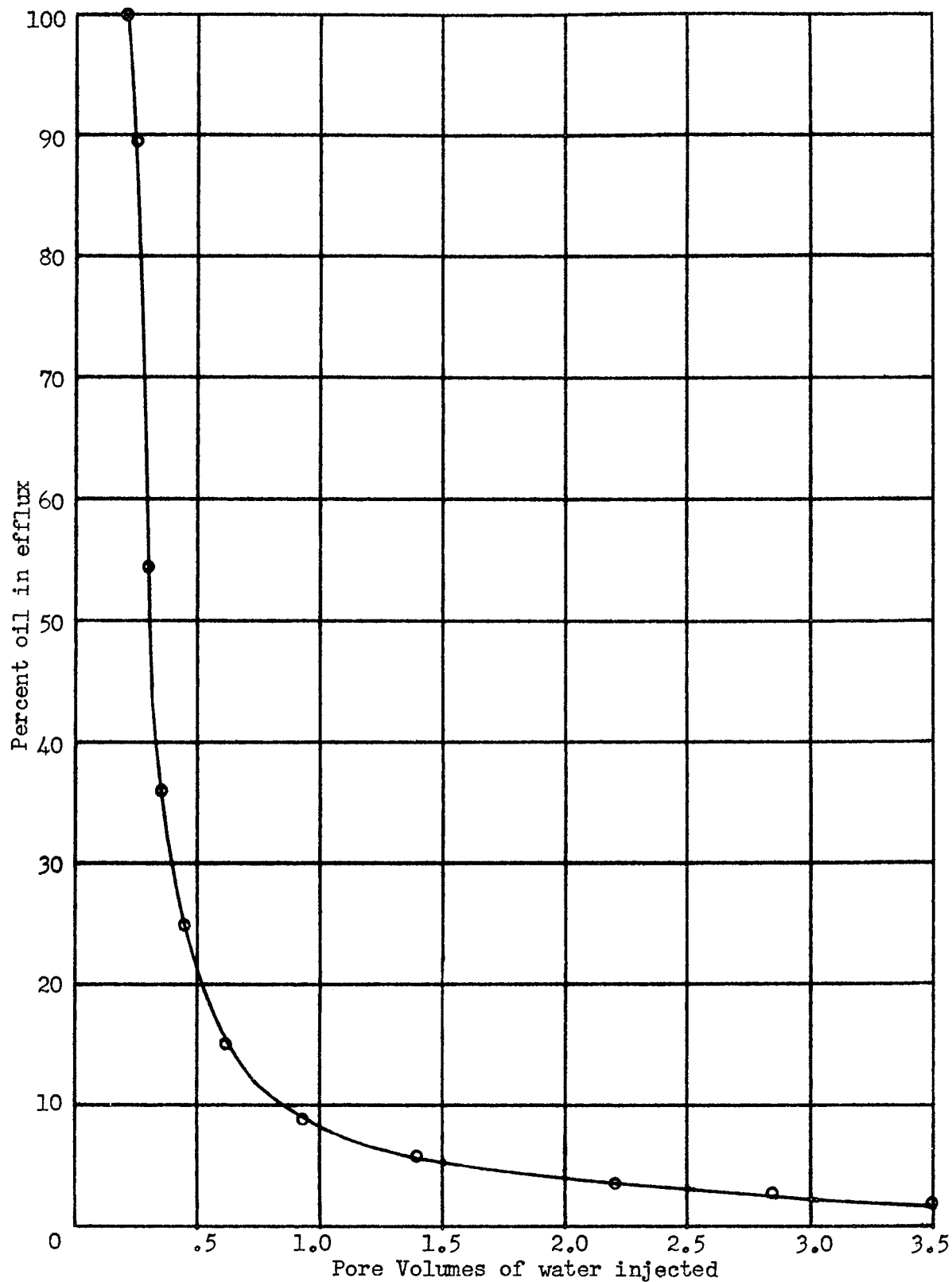


Fig. No. 12, Run No. 6
Percent oil in efflux versus Pore Volumes of water injected
Flend No. 3, Viscosity ratio oil/water 7.5

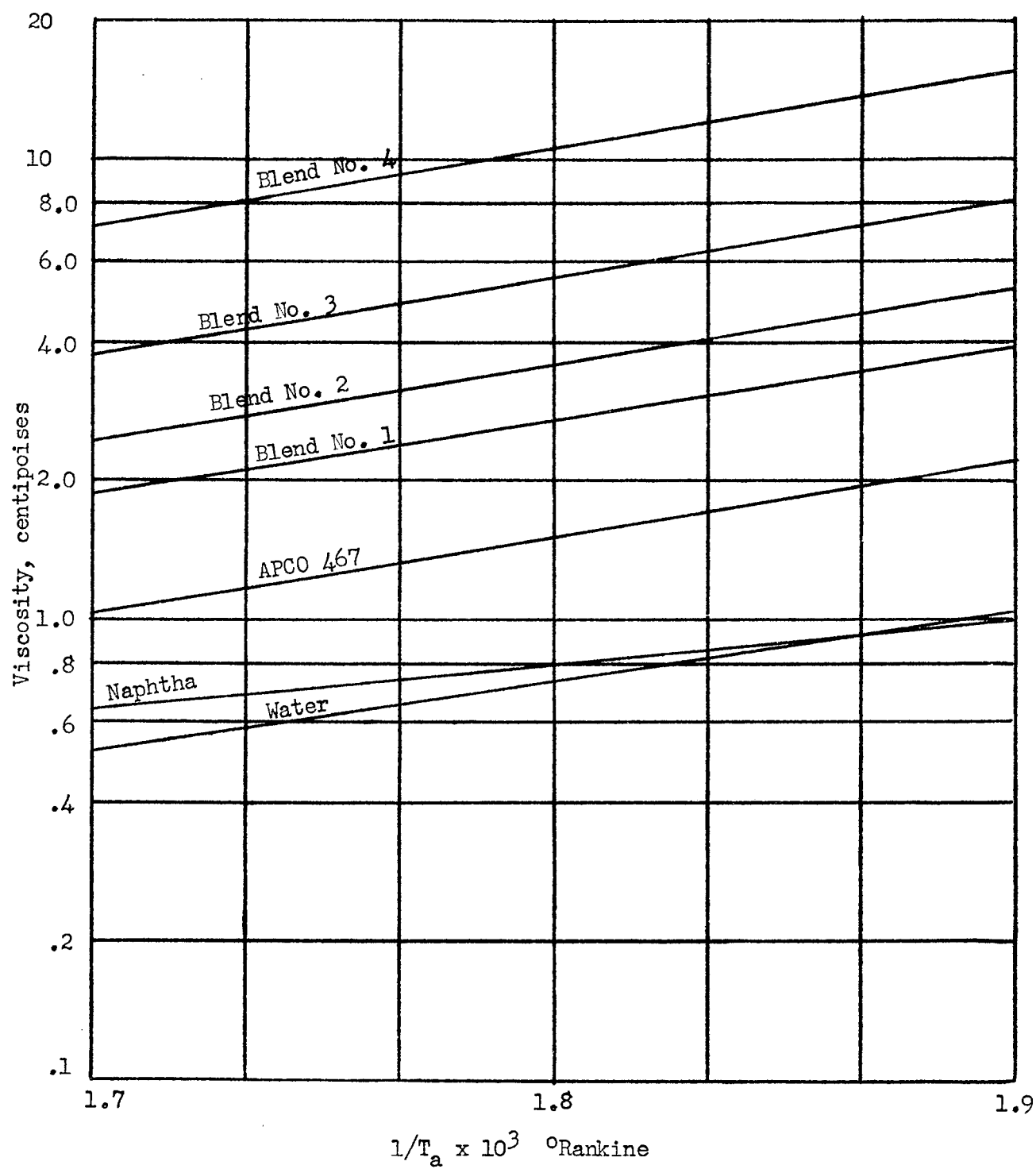


Fig. 13. Viscosity versus temperature

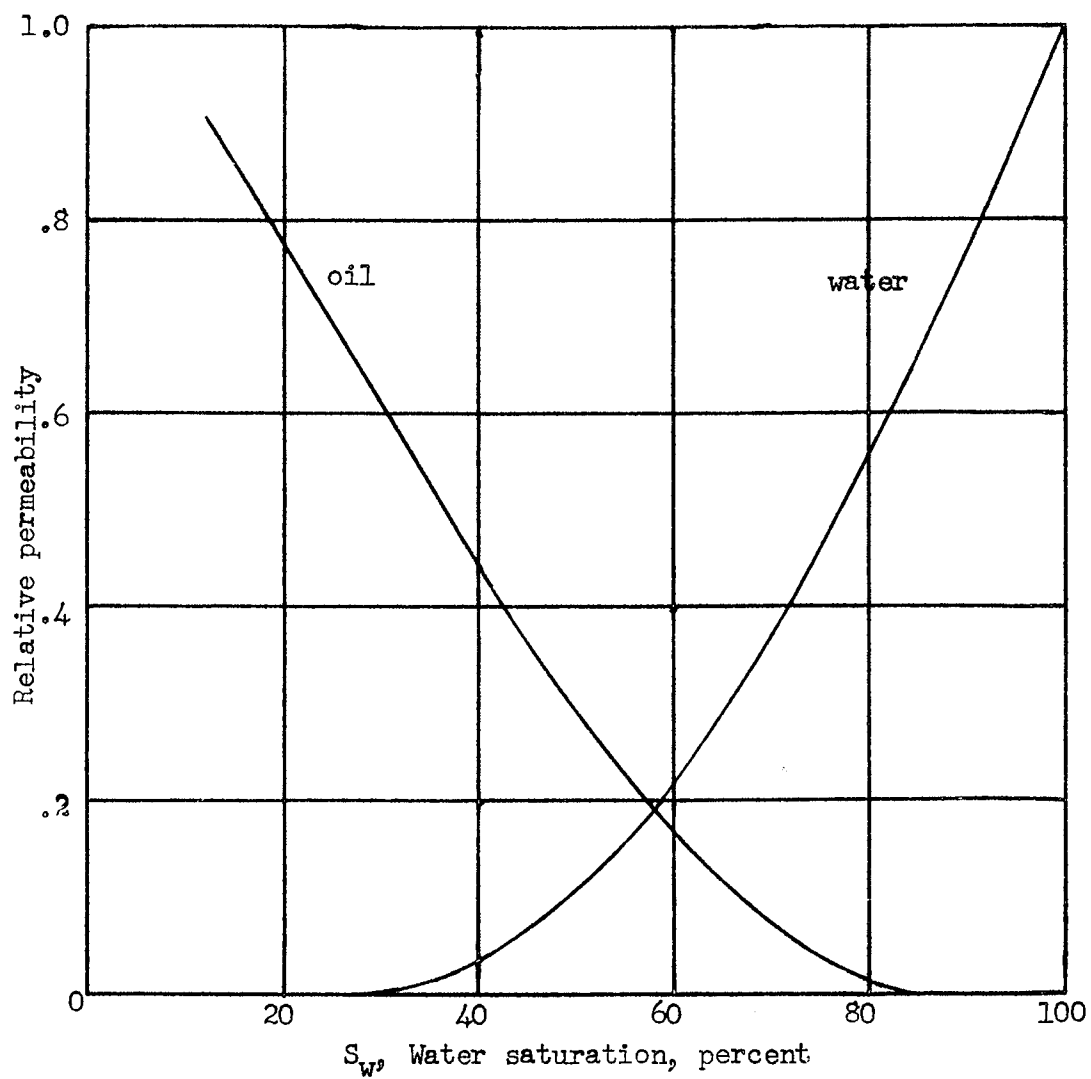


Fig. 14. Relative permeability versus water saturation

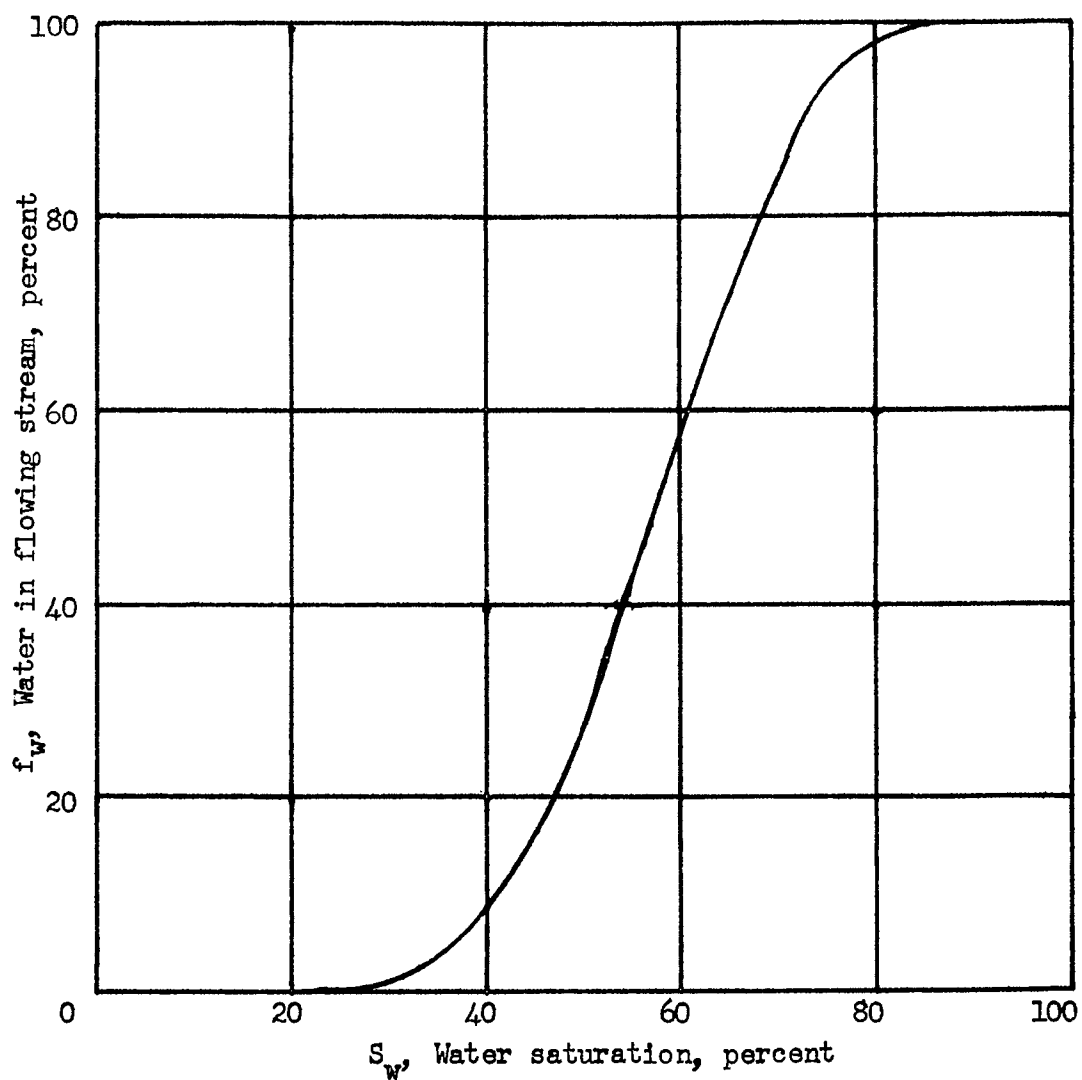


Fig. 15. Percent water in flowing stream versus water saturation

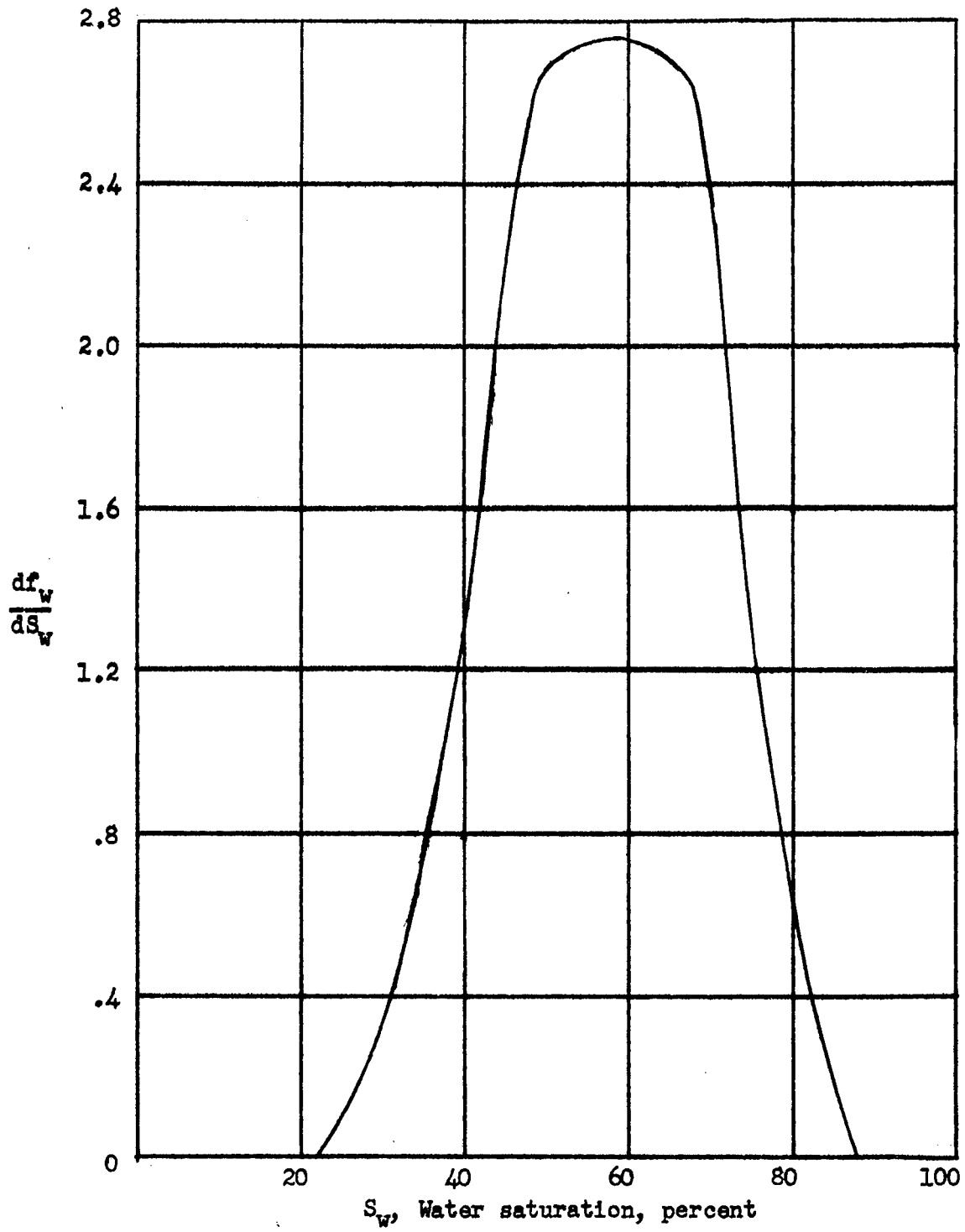


Fig. 16. $\frac{df_w}{ds_w}$ versus water saturation for theoretical calculations

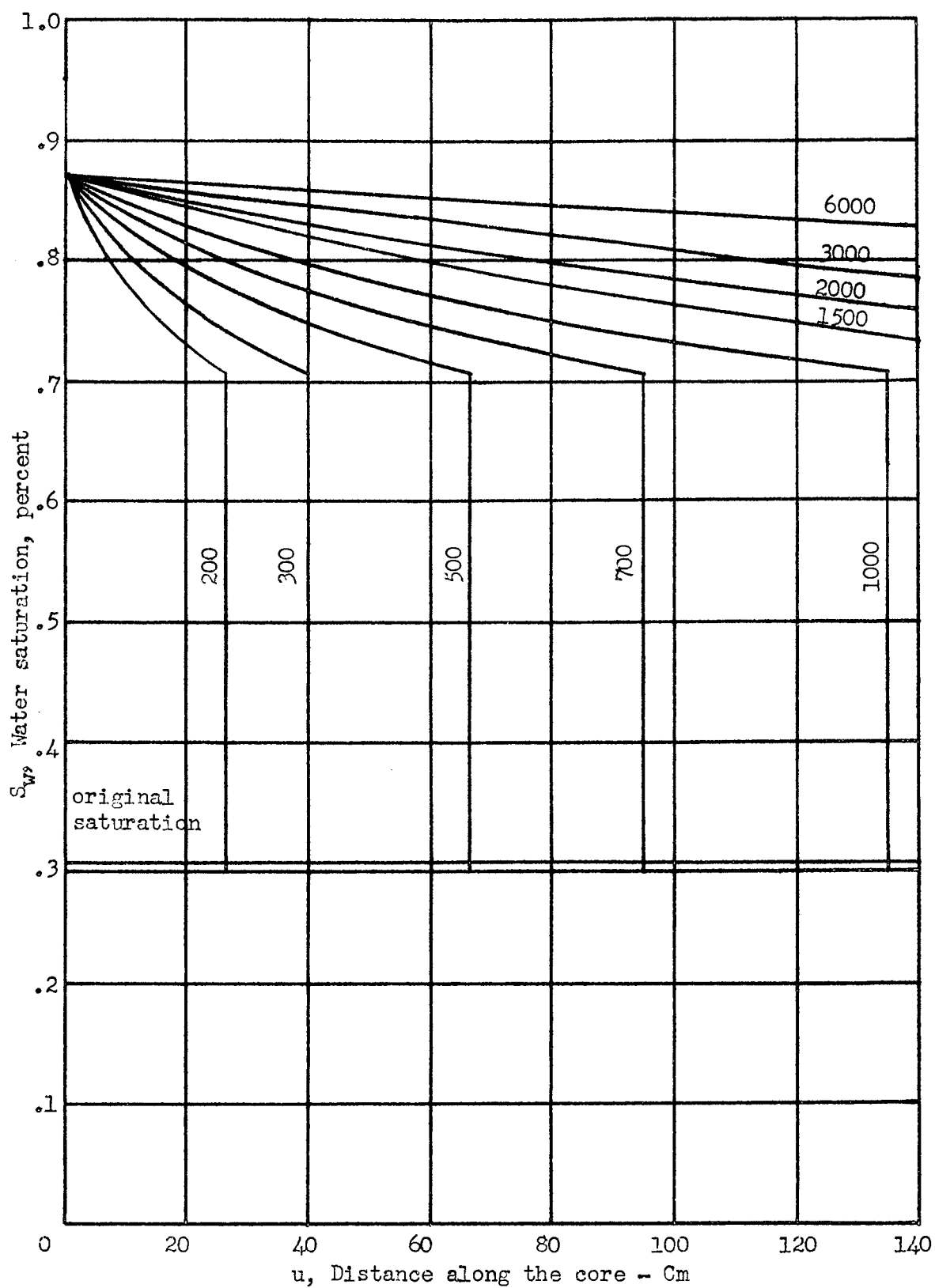


Fig. 17. Water saturation versus distance along core

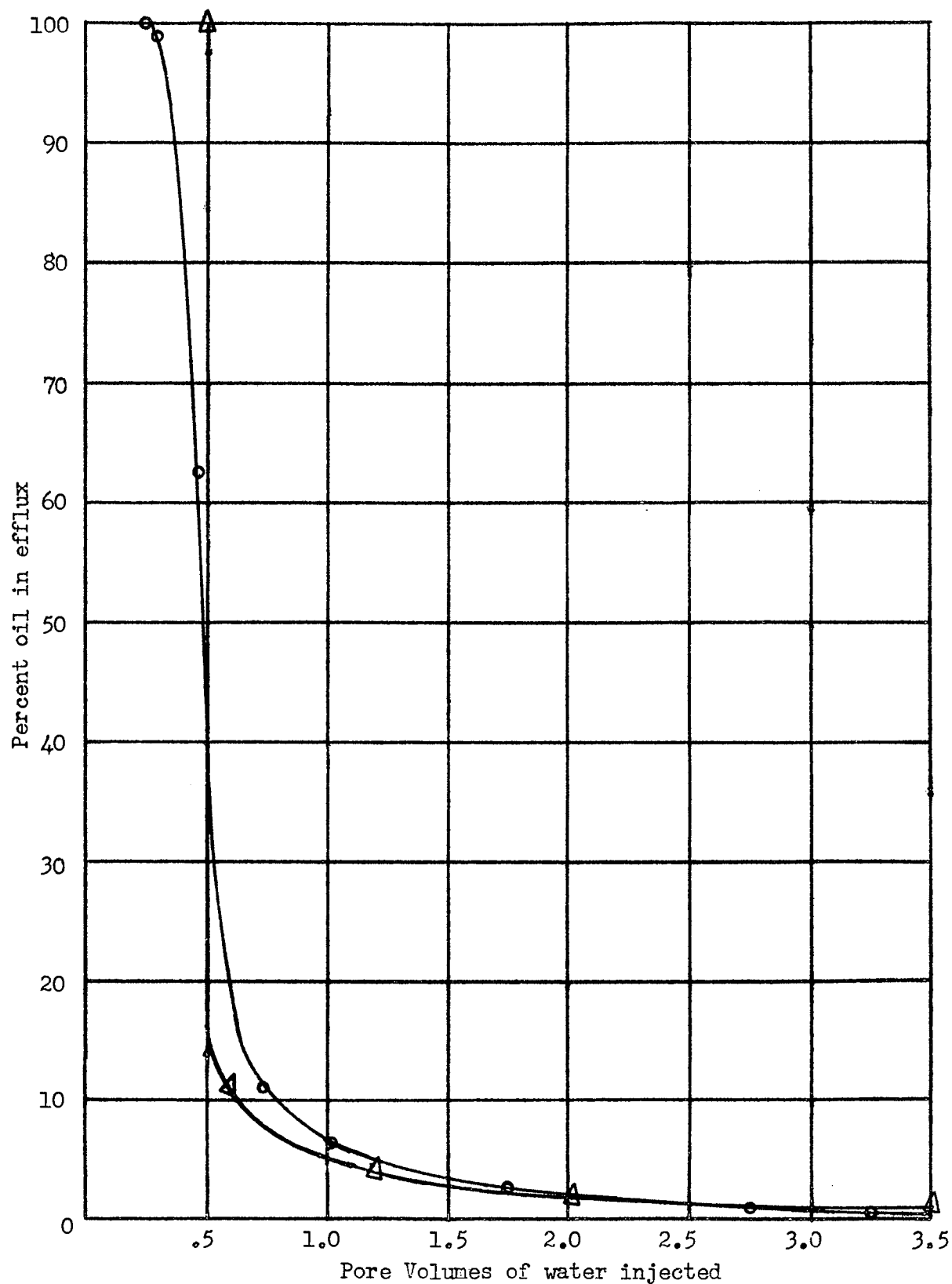


Fig. 18. Comparison of calculated and experimental data for Δ Buckley and Leverett's theoretical calculations and \circ Run No. 4

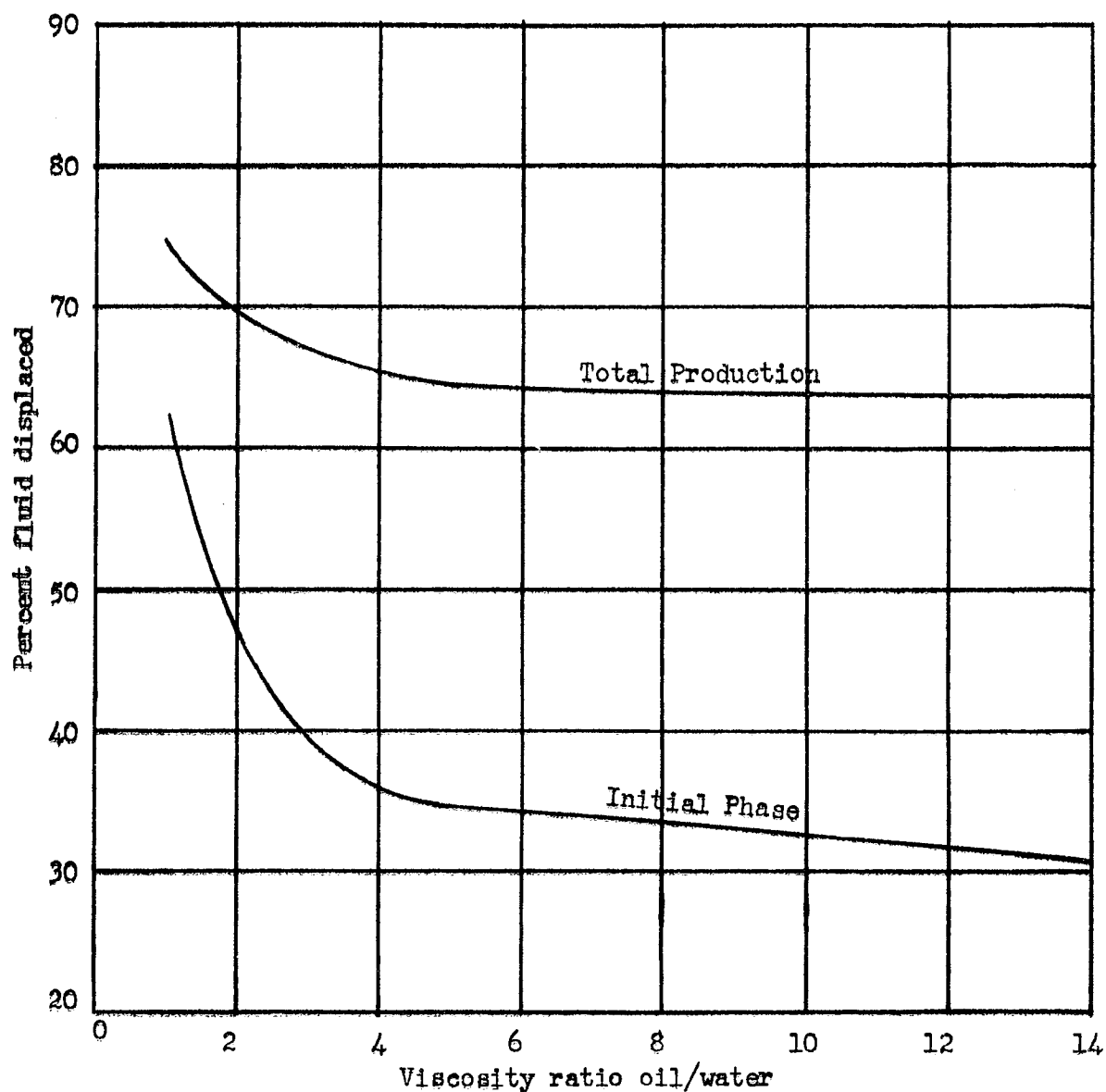


Fig. 19. Percent fluid displaced versus viscosity ratio oil/water for oil produced during the initial phase and the total produced oil.

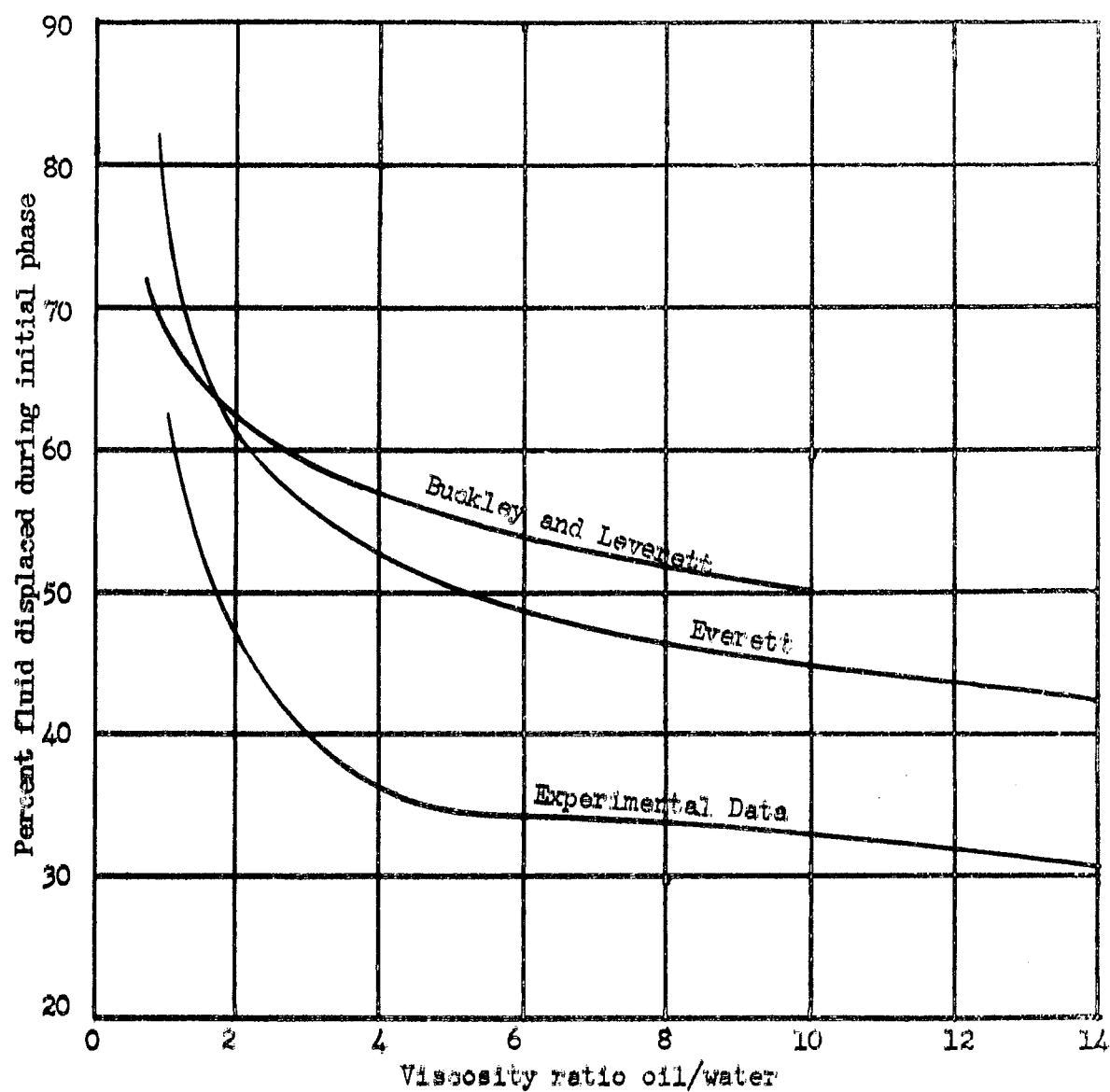


Fig. 20. Comparison with Buckley and Leverett's and J. P. Everett's data on efficiency of initial phase of production

Chapter VI

Analysis of Problem

In making a theoretical approach to the problem at hand, Buckley and Leverett's¹⁰ analysis on mechanism of fluid displacement in sands was used in calculating the theoretical results that would be obtained on such a problem as this.

In taking into consideration only unidirectional flow through a small element of sand within a continuous sand body the following material balance may be set up:

$$\left(\frac{\partial S_w}{\partial \theta}\right)_u = - \frac{q_t}{\phi A} \left(\frac{\partial f_w}{\partial u}\right)_\theta \quad (1)$$

Where

S_w = saturation of displacing fluid

θ = time

u = distance along path of flow

q_t = total rate of flow through section

ϕ = porosity

A = cross-sectional area

f_w = fraction of flowing stream comprising displacing fluid

Which can be transformed to:

$$\left(\frac{\partial u}{\partial \theta}\right)_{S_w} = \frac{q_t}{\phi A} \left(\frac{\partial f_w}{\partial S_w}\right)_\theta \quad (2)$$

This equation indicates that the rate of advance of a plane of fixed saturation is proportional to the change in composition of the flowing stream caused by a small change in the saturation of the displacing fluid.

¹⁰ Buckley and Leverett, Loc. Cit.

By neglecting effects due to gravity and capillary pressure difference, f_w the fraction of the displacing fluid in the flowing stream can be expressed in terms of the properties of the system by the equation:

$$f_d = \frac{1}{1 + \frac{K_o \mu_w}{K_w \mu_o}} \quad (3)$$

Where: K_o = permeability of the sand to oil
 K_w = permeability of the sand to the displacing fluid.
 μ_o = viscosity of oil
 μ_w = viscosity of displacing fluid.

Since time and the necessary equipment were lacking to determine completely the relations between relative permeabilities to oil and water at respective saturations, it was decided to use the end points obtained during the flooding of the core to determine the zero relative permeabilities and saturations at this point for the core. This residual saturation was obtained when the percent of flooded fluid in the efflux was zero, or when the relative permeability to the flooded fluid was zero.

By using the end points obtained as explained and Buckley and Leverett's curve, which was drawn from several experiments on various sands, a relative permeability curve, Fig. 14 was constructed which should be fairly representative of the core used in this test.

With equation (3) and the relative permeability curve described above, the relation between f_w and S_w may be derived and subsequently between $\frac{\partial f_w}{\partial S_w}$ and S_w for a given system. In the assumed condition of no gravitational or capillary effects, f_w for a given sand and fluids varies only slightly with factors other than S_w and it may be assumed that under these conditions $\frac{\partial f_w}{\partial S_w}$

is also uniquely related to S_w , being constant for fixed S_w . Referring back to equation (2), a plane, at which the saturation is S_w , moves along the path of flow at a constant velocity equal to $\frac{q_t}{\phi A} \frac{df_w}{dS_w}$. The basic equation relating position along the path of flow, saturation, and time then may be written:

$$\Delta u = \frac{q_t}{\phi A} \left(\frac{df_w}{dS_w} \right) \Delta \theta \quad (4)$$

or in terms of Q_t , the total amount of displacing fluid entering the system:

$$\Delta u = \frac{Q_t}{\phi A} \left(\frac{df_w}{dS_w} \right) \quad (5)$$

As an example of the application of equation (5) a qualitative determination of the process of displacement was carried out on Run No. 4. Fig. 14 shows the relation between permeabilities of the sand to the oil and the displacing fluid, which in this case was water, in a sand containing only oil and water. Fig. 15 shows a plot of f_w and S_w obtained by means of equation (3) and the properties of the system used. $\frac{df_w}{dS_w}$ versus S_w , as shown in Fig. 16, was obtained by taking slopes from the f_w versus S_w curve.

For comparison with the experimental results obtained in this work, percent oil in efflux versus quantity of water injected was calculated for Run No. 4 by means of equation (5). The above relationship was obtained by graphical methods as shown in Fig. 17. In making these calculations, the quantity of water injected was assumed and the relationship between S_w and u was plotted. By means of this initial calculation the percentage of water saturation was obtained for the initial phase of the displacement.

The plot of u versus S_w would give a curve similar to the $\frac{df_w}{dS_w}$ versus S_w curve, since for a given quantity of water injected all the terms in equation (5) would be constant except $\frac{df_w}{dS_w}$. The initial saturation of the core would

be plotted as a straight line on this curve, thus giving a triple valued function for S_w , which is a physical impossibility. A material balance was used to find the position of the initial phase, because the curve must be discontinuous since it cannot be triple valued.

The discontinuity at the initial phase would maintain a constant water saturation as it moves along the core. As a result of this, only a partial solution was carried out at this point as this would give the desired oil percent in the efflux. To obtain the percent oil in efflux from the above solution, a distance along the u axis was taken corresponding to the length of the core and the water saturations were read for the different quantities of water injected in calculating the curves for Fig. 17. With these saturations obtained as above, the fraction of water flowing in the efflux could be obtained from the f_w versus S_w curve, which would in turn give the oil fraction.

A close approximation to actual conditions can be obtained from Fig. 17 by giving the initial phase line a more gradual slope at the top and bottom because capillary pressures would cause this more gradual gradation from one phase to the other.

Chapter VII

Summary

This study of the displacement of oil by water in a partially consolidated sandstone core was made by using a synthetic core constructed from an initially high quartz content sand.

By constructing a chemically clean synthetic core, using a constant temperature bath and keeping inlet pressure constant, the effect of varying viscosity ratios could be studied since the other properties of the system were kept as constant as possible.

All displacement tests run for this work were made on an oil-filled core with original connate water saturations. The different viscosity ratios were obtained by varying the oils used and keeping the water viscosity constant.

The oils used in this work were refined, low vapor pressure oils, and distilled water was used both for the connate water saturation and the displacing fluid for the oil. Oil to water viscosity ratios were varied from approximately 1 to 10.

The data gathered in this work was used to study the effect of varying viscosity ratios on the displacement of oil by water from porous media which contain connate water. It was concluded that variation in viscosity ratios has a greater effect upon recovery efficiencies when based upon initial phase production than if based on total oil produced when all runs were carried to one percent oil in efflux. It also was found that connate water tends to lower recovery efficiency as compared to results obtained by previous investigators.

Chapter VIII

Discussion and Conclusions

The experimental results as obtained from these tests are tabulated in Tables I through VI and these tables contain the original data. Fig. 1 through 12 are plots of this data to afford a better comparison of the various runs.

The efficiency of initial phase displacement is of primary interest at the present time since it is not economically feasible to carry production much past this phase under actual field conditions. From Fig. 19 it can be seen that in the viscosity range of 1 to 4 a slight change in viscosity may have a large effect upon the recovery efficiency for initial phase displacement, also it may be seen from the same figure that this effect is considerably less when recovery efficiency is based on total oil recovery.

Fig. 7 through 12 show the rapid decrease in percent oil in efflux after the initial phase of production has been completed. These graphs also show that percent oil in efflux drops off very rapidly on the completion of the initial phase production as viscosity ratios approach 1.

The main disagreement between the calculated results and the experimental data was during the initial phase, as illustrated by Fig. 18. The curves seem to be in good agreement for the secondary phases of displacement.

The decrease in initial displacement efficiency with original connate water saturation when compared to the displacement efficiency with no original water saturation might be explained by two effects introduced by the original connate water saturation.

1. Since the readiness with which a fluid flows through a sand increases with saturation, the initial water saturation would tend to decrease the flow of oil and increase water flow, thereby decreasing initial

phase flooding efficiency.

2. Buckley and Leverett state that if initial water saturations are high enough, no initial phase will be formed and only a scrubbing action will take place. In following this line of reasoning, water saturations up to this point might have the effect of decreasing the efficiency of the initial phase while not completely preventing its formation.

From the examination of graphs contained in this report, and the above discussion, the following conclusions may be drawn:

1. Variations in viscosity ratios have a definite effect upon recovery efficiencies of displacement of oil by water during the initial phase, with efficiencies decreasing rapidly at first with increase in viscosity ratio, then tending to level off at higher ratios.
2. The lower viscosity ratios, though having higher efficiencies during the initial phase, displaces very little oil during the secondary stages of production whereas the higher viscosity ratios have lower initial phase recovery but they tend to produce more oil during the secondary phases than the higher viscosity ratios.
3. It was found that the final phase displacement efficiencies were not so sensitive to variations in viscosity ratios as the initial phase displacement efficiencies.
4. The recovery efficiencies obtained from this investigation were considerably lower than those obtained by Everett, Calhoun, and Gooch¹¹ when conducting similar tests without considering the effect of connate

¹¹ Everett, J. P., Gooch, F. W., and Calhoun, John C. "Liquid-Liquid Displacement in Porous Media as Affected by the Liquid-Liquid Viscosity Ratio and Liquid-Liquid Miscibility." Transactions, American Institute of Mining and Metallurgical Engineers. (1950) Vol. 189, pp. 215, 224.

water saturation. The recovery efficiencies obtained from this investigation were also lower than the theoretical efficiencies as calculated by Buckley and Leverett.

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THESIS TITLE: THE EFFECT OF VARYING VISCOSITY RATIOS ON
DISPLACEMENT OF OIL BY WATER IN POROUS MEDIA
WITH CONCENTRATE WATER

NAME OF AUTHOR: CHARLES THOMAS EVANS

THESIS ADVISER: LADISLAUS J. FILA

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NAME OF TYPIST: Fern B. Hall

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