EFFECT OF FREE GAS SATURATION ON OIL RECOVERY BY WATER FLOODING

C. R. HOLMGREN AND R. A. MORSE, JUNIOR MEMBERS AIME, STANOLIND OIL AND GAS CO., TULSA, OKLA.

ABSTRACT

The production of oil by water flooding can be substantially increased by the maintenance of free gas saturation in the reservoir during the flooding operation. This effect is accomplished by the alteration of oil relative permeability characteristics and the occupation by gas of pore space that would otherwise be filled with residual oil. The amount of reduction in residual oil can be calculated from appropriate water-oil relative permeability characteristics.

This paper presents experimental data in support of the foregoing conclusions and an example of the calculations. The microscopic pore saturation concepts of the mechanism are discussed. A method of practical application to field floods is presented together with discussion of certain limitations.

INTRODUCTION

The presence of free gas has been reported by a number of investigators to significantly affect the oil recovery which can be obtained from sandstone flow systems by water flooding.[1,2,3,4,5] The effect of gas, noted in every instance, has been to cause lower residual oil saturations than could be obtained by water flooding the same systems in the absence of free gas. The degree of improvement in recovery has been observed to vary widely, depending on the systems used and the conditions of the tests. The increased oil recovery obtained because of the presence of gas during a water flood has been variously attributed to changes in physical characteristics of the oil, selective plugging action of the gas, inclusion of oil mist in the free gas phase, and the additional sweeping or driving action of the free gas.

All but the first of these suggestions imply changes in the displacement mechanism. The change in viscosity and interfacial tension of the oil phase, within the pressure range used for all the experimental work, is certainly not sufficient to account for the differences in residual oil saturation noted unless there is a drastic change in the displacement process.

One other effect which logically seems capable of causing differences in residual oil saturation of the magnitude noted in the experimental work is that of simple replacement. In a water-wet system containing oil, water, and gas, it is to be expected that the gas will exist inside the oil. This is the position of minimum free surface energy, since the gas-oil interfacial tension will be less than the gas-water interfacial tension. There is no apparent reason to expect that the existence of free gas within the oil phase should alter the saturation at which the non-wetting phase (now oil and gas) should become discontinuous and hence trapped so as to be unrecoverable by direct displacement by water. If this is the situation, then trapping of a certain percentage of gas saturation during water flood should result, at infinite water-oil ratio, in a like reduction of oil saturation below that attainable by flooding in the absence of free gas. It is visualized that the gas will exist as bubbles inside the discontinuous residual oil as illustrated in Fig. 1, with the size of the oil bubbles being substantially unchanged due to the presence of the gas. As a practical matter, it can be anticipated that the presence of a free gas saturation inside the oil phase will reduce the relative permeability to oil which will exist at any particular water saturation. This reduction will be caused by two factors — the addition of the gas-oil interface, and the reduction of area available for oil flow in the pores containing gas. This reduction in oil permeability at any particular water saturation will result in water breakthrough at a lower water satu-

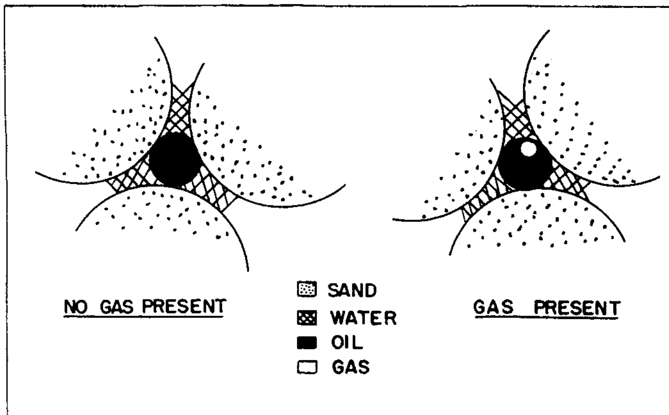

FIG. 1 — CONCEPT OF OIL AND GAS LOCATIONS IN PORE SPACE AT RESIDUAL OIL SATURATION.

[1]References given at end of paper.

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ration and higher water-oil ratios for a given water saturation following breakthrough, than would be obtained if gas were not present.

It has been impossible to quantitatively evaluate, from the available experimental work, the effects of free gas on water flooding because of one complicating factor common to all experimental work; that of unmeasured variations of gas saturation at the water flood front. Water flooding of a linear system, partially saturated with oil and gas, results in the formation of an increasingly wide oil bank ahead of the injected water. The moving oil bank will displace gas ahead of it, reducing the gas saturation to some residual value immediately behind the front of the oil bank. The movement of the oil bank will cause the pressure on the residual gas to be increased above the value at which it was trapped. The amount that the pressure on the gas will be increased, before the water flooding front reaches it, will depend on the width of the oil bank, the oil permeability, and the flow rate. As the pressure increases, the gas will be reduced in volume due to compression and solution. If the pressure is increased enough between the time the gas is trapped and the arrival of the water flood front, all of the gas may be put into solution in the oil, causing the system to revert to one of two liquid phases. The gas saturation existing at the water flood front may have any value between zero and the maximum residual gas trapped at the front of the advancing oil bank. If improved water flooding oil recovery is dependent on the existence of a free gas phase, the mere existence of an initial gas saturation before flooding begins would not necessarily insure that lower oil saturations could be obtained than could be obtained by flooding a completely liquid saturated system.

One way to avoid the complication of varying gas saturation during the water flooding process would be to conduct the flood at a pressure differential which is very small compared to the absolute pressure of the system. In this way the residual gas saturation at the water flood front can be kept substantially the same as that in the entire oil bank. The amount of this residual gas saturation should then be merely a function of the relative permeability characteristics of the sand and the saturation conditions prior to the flood.[6] Experimental work reported in this paper was conducted under these conditions with the specific objective of isolating the effects of a static free gas phase on water flooding recovery as differentiated from any alteration in the displacement mechanism occasioned by the presence of mobile gas.

APPARATUS AND MATERIALS

The core in this investigation was five in. in diameter and five ft long. It was quarried from an outcrop near Sand Springs, Okla., and ground to a cylindrical shape. This sandstone, which is known as the Nellie Bly, is well consolidated and has an average porosity of about 27.4 per cent. The average specific permeability to water of this core was 612 md.

Piezometer rings made of brass cups and tubing were placed on the core at intervals. End plates, thermocouples, and an additional conductivity ring were attached and the assembly sealed with a viscous rubber compound which set up into a hard impervious coating. This core assembly was mounted in a heavy steel housing. Outlets from the piezometer rings were electrically insulated through the housing so that piezometer rings served as conductivity electrodes as well as pressure measurement taps.

Fig. 2 is a schematic diagram of the apparatus, which consists of the core assembly, liquid-gas separators, recording flowmeters, filters, and sight gauges. Means were provided to record differential pressures across any desired interval or intervals along the core. Electrical conductivity, from which brine saturation could be obtained, could also be measured across any desired interval. The entire apparaus was designed to operate at pressures up to 1,000 psi and temperatures to 150°F.

The oil used in these experiments was a close-cut naphtha having a density of .767 gm/cc and a viscosity of 0.990 cp at 80°F. In the experiments the oil was saturated with methane at pressures varying from 388 to 517 psi, and under these conditions, the approximate viscosity range was from .75 to .85 cp.

The water was a prepared brine having approximately 33,000 ppm *NaCl*. Sodium nitrate was added to inhibit corrosion and the *pH* value was adjusted to about 7.7. The gas used was commercial grade (96 per cent) methane.

PROCEDURE

The core was initially saturated 100 per cent with brine, the reference electrical conductivity was obtained, and the brine saturation reduced to a value in the range of 26.4 to 30 per cent by flooding with oil. The oil circulated to reduce the water saturation was saturated with methane. When the water saturation had been reduced to a sufficiently low value, with the remaining pore volume being saturated with live oil, the core was further prepared for the flood tests by one of the three following methods:

1. A gas drive was conducted at constant pressure until the gas saturation was increased to a sufficiently high value that subsequent oil flooding would obtain the desired residual gas saturation. Fig. 3 is a plot of the relationship between the maximum gas saturation obtained by the gas drive versus the residual gas saturation retained in the core following oil flooding. Once the desired maximum gas saturation was obtained, gas-saturated oil was injected into the core under low pressure differentials in order to displace excess free gas. Circulation of the oil was maintained until no further gas was produced from the core. Once the residual gas saturation became stabilized, the core was ready for water flooding.[6]

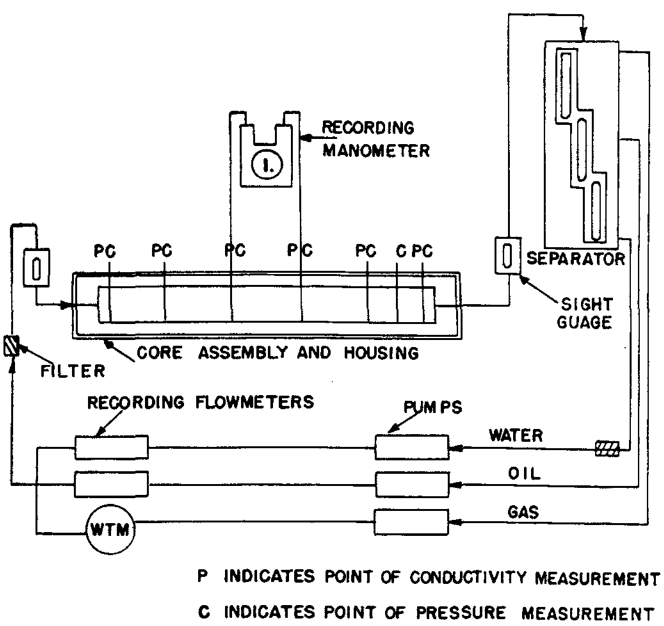

FIG. 2 — SCHEMATIC SKETCH OF EXPERIMENTAL EQUIPMENT.

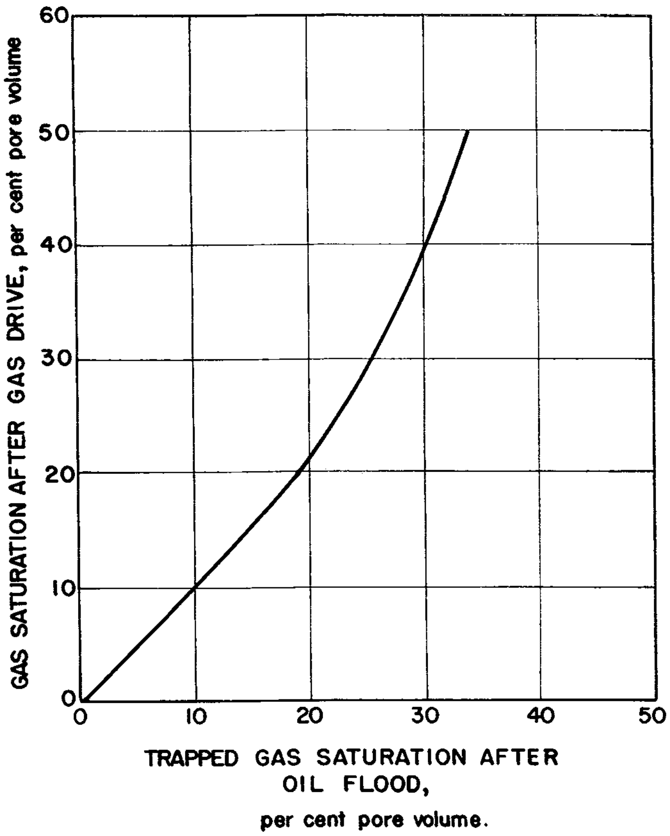

FIG. 3 — RELATIONSHIP BETWEEN MAXIMUM GAS SATURATION OBTAINED BY GAS DRIVE AND TRAPPED GAS SATURATION AFTER OIL FLOOD.

2. A procedure identical with (1) above was used to establish a certain gas saturation which was followed by pressure reduction in the system to allow expansion of the trapped gas saturation. The amount of pressure reduction was small enough that no free gas was produced due to expansion of the trapped gas. Oil was circulated at the lower pressure to remove any super-saturated liquid and to insure that the gas saturation had not been increased to the point where it would be produced upon water flooding.
3. Previous to one flood the system was subjected to an internal gas drive down to a pressure of 300 psia from an original saturation pressure of 500 psia.

The fluids were contained in a closed system after the establishment of 100 per cent liquid saturation so that any variation in either oil or water content was reflected in a change in level in the production separator. This separator was calibrated so that production could be measured to an accuracy of 0.1 per cent of the pore volume. The average gas saturation prior to water flooding was determined by means of a material balance in the liquid system. Once the core had been prepared as outlined above, the water flood was conducted by injection of water at rates low enough that the maximum pressure gradient in the flow system was less than 2.7 psi/ft. Flooding was continued until the water-oil ratio was above 100.

It was originally planned to obtain free gas saturations below the equilibrium value, which was expected to be of the order of magnitude of seven to eight per cent, by a slight reduction of pressure on the system saturated with water and gas-saturated oil. It was believed, on the basis of experimental work reported by other investigators, that such a process would result in the most uniform possible distribution of free gas. However, initial attempts to obtain gas saturation by this means resulted in failure. Equilibrium vaporization data indicated that only slight pressure reductions would be necessary to form gas saturation of less than ten per cent. Such pressure reductions on the system resulted in almost no oil production and hence no free gas formation. It was found that the pressure could be reduced in excess of 50 lb below the equilibrium bubble point prior to any significant production. Reduction of the pressure to the point where oil production started resulted in gas saturations which were not reproducible from one run to the next. Supersaturation of the oil below the bubble point pressure, as indicated here, is not a peculiar characteristic of this rock-fluid system. It has been observed in every system where investigation of the phenomenon has been made, and is presently a subject of investigation in this laboratory. The technique was then revised to obtain a stable free gas saturation by means of gas drive followed by oil flooding at constant pressure, as described above.

After the water flood, the final gas saturation was determined as a check on original material balance calculations. This was done by circulating dead oil, furnished from a container external to the regular flow system through the core and into the separator. The difference between the amount of liquid produced into the separator and the amount of dead oil injected into the system, at the time when the core reached 100 per cent liquid saturation, represented the amount of gas in the system at the start of the dead oil flood, since the dead oil absorbed and replaced the free gas in the pore space. At the finish of a flood, the dead oil was flushed from the core by gas-saturated oil, and the water saturation reduced by further oil circulation, making the core ready for another experimental cycle.

RESULTS

Tables I and II summarize the pertinent data on saturation conditions prior to water flooding, at water breakthrough, water-oil ratio of approximately 100, and final conditions. Portion of this data are shown graphically in Fig. 4.

The flood in Run 1 shown in Table I was conducted with the core initially 100 per cent saturated with water and live oil to establish a standard of comparison for the later tests in which free gas was to be present prior to flooding. The data from this run check very closely with the performance of a number of other floods in which the oil was not saturated with gas.

Table I

Summary of Data for Floods in Which Static Gas Saturation Was Obtained by Oil Flood Only

Run Number	1	2	3	4	5	6
Original Water Sat., % Pore Vol	30.0	28.3	28.4	27.7	27.2	27.0
Original Oil Sat., % Pore Vol	70.0	63.0	62.7	70.0	47.5	56.0
Original Gas Sat., % Pore Vol	0	8.7	8.9	2.3	25.3	17.0
Average Outlet Pressure, psia	517	465	465	388	505	490
Oil Prod. to Breakthrough, % Pore Vol.	33.0	31.2	33.0	36.8	26.0	30.2
Total Oil Produced, % Pore Vol	36.0	33.1	36.0	37.9	30.7	32.7
Water Sat. at Breakthrough, % Pore Vol	63.0	59.5	61.4	64.5	53.2	57.2
Residual Oil Sat. (at 100-1 water-oil ratio) % Pore Vol	34.0	29.9	26.7	32.1	18.8	23.5
Water Saturation, % Pore Vol. (at 100-1 water-oil ratio)	66.0	62.1	64.1	66.4	56.7	59.1
Final Water Saturation, % Pore Vol	66.0	62.1	64.1	66.4	58.7	60.1
Final Gas Sat., % Pore Vol. (by difference)	0	8.0	9.2	1.5	24.5	16.6
Final Gas Sat., % Pore Vol. (by dead oil replacement)	..	..	9.2	2.1	24.6	17.2
Reduction in Resid. Oil from Run 1 % Pore Volume	...	4.1	7.3	1.9	17.2	10.7
Average Flow Rate, cc/min	1.62	1.40	1.47	1.25	1.50	1.52
Total Water Throughput, Pore Vols	.613	.592	.626	.669	4.381	1.240

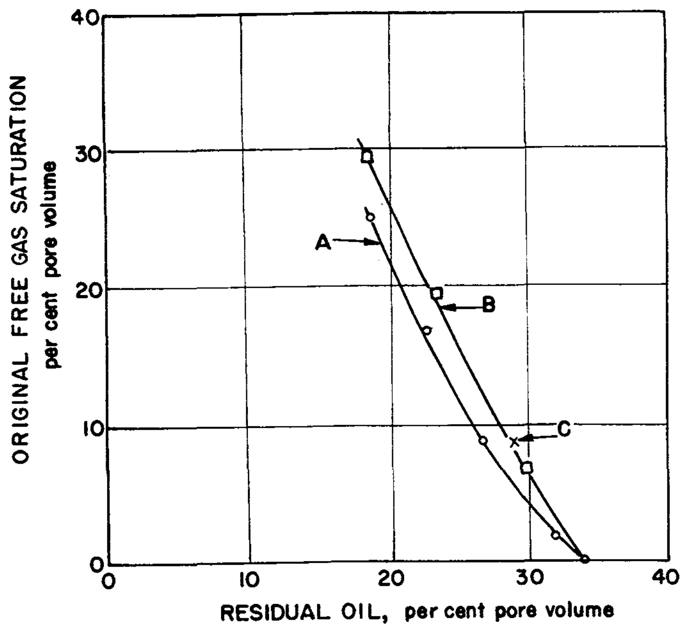

FIG. 4 — RELATION BETWEEN FREE GAS SATURATION AND RESIDUAL OIL SATURATION AT 100:1 WATER-OIL RATIO. CURVE A — GAS TRAPPED BY OIL FLOOD ONLY; CURVE B—GAS TRAPPED BY OIL FLOOD AND EXPANDED BY PRESSURE REDUCTION; POINT C — GAS ESTABLISHED BY INTERNAL DRIVE.

The initial gas saturation for the series of tests summarized in Table I was established by gas driving followed by oil flooding with no change in pressure. It is believed that this method yields the most uniformly distributed gas saturation possible. It will be noted from these tests that at low gas saturations, the reduction in oil saturation below that of the reference run is only slightly less than the free gas saturation. Each succeeding increment of initial free gas saturation results in a smaller decrease in oil saturation, at reasonable water-oil ratios, until, at the highest gas saturation used (25.3 per cent), the total reduction was 15.2 per cent of the pore volume. This trend has been anticipated and is caused by the decreasing relative permeability to oil occasioned by increasing gas saturation.

An attempt[*] was made, in Run 5, to check the postulation that the total saturation of the non-wetting phase or phases (oil or oil plus gas) ultimately attainable at infinite water-oil ratios should be independent of the amount of free gas. This water flood was conducted for a period of ten days with a resultant oil production increase of two per cent above that at a water-oil ratio of 100. The rate of oil production was so low that several weeks of additional flooding time would have been necessary to reach the same water saturation as that obtained on the reference flood. Because of the excessively long time involved, the flood was discontinued without establishing the relationship between gas saturation and residual non-wetting phase saturation at zero permeability to oil. This point has little significance from the standpoint of application to field flooding, but should be established to clarify present concepts on the microscopic aspect of fluid displacement.

It was recognized that the relationship between residual oil and original gas saturation was not unique but would depend on the distribution of the saturation.[6] For example, the effect on oil recovery of an average gas saturation of 20 per cent resulting from 33 per cent saturation in only 60 per cent of the pore openings would be expected to differ from that of the same average gas saturation distributed uniformly in every pore. It is tentatively believed that the extremes possible in gas saturation distribution are those obtained by

(1) flooding at constant pressure from an initial maximum gas saturation, or

(2) displacement of liquid by increasing gas saturation.

Accordingly, the initial gas saturations for the runs summarized in Table II were established by trapping a certain amount of residual gas by oil flooding and expanding that gas by pressure reduction.

The data from this series of tests, shown as Curve *B* in Fig. 4, clearly demonstrate that a given gas saturation established by the gas expansion technique resulted in somewhat less increased oil recovery than the same saturation established by the flooding at constant pressure technique. However, by either method, the residual oil saturation could be very substantially reduced from the case in which no free gas was present.

In one test, Run 10, the initial gas saturation was established by internal gas drive (Point *C*, Fig. 4).

INTERPRETATION OF RESULTS

If the effect of static free gas saturation during water flooding is merely replacement of residual oil combined with reduction of oil permeability, it should be possible to calculate these effects by means of the frontal drive method of Buckley and Leverett.[7] The only complication is that the necessary water-oil relative permeability relationship must be measured with the proper static gas saturation. In order to determine the applicability of such a procedure, relative permeabilities were measured at 25 per cent gas saturation in the system upon which the above discussed floods were conducted. The preliminary treatment of the core to establish the gas saturation was the same as that used for the first series of tests — gas drive followed by oil flood at constant pressure. After the gas saturation was established, oil and water were injected simultaneously into the core at fixed ratios until saturation equilibrium was established at each flowing ratio. Equilibrium was determined by stabilization of electrical conductivity and pressure differentials. The saturations and pressure drops for the relative permeability calculations were measured in the center foot of the five-ft core to eliminate disturbing end effects. Flow rates were low enough so that the over-all pressure differentials were less than ten psi. The relative permeability data at 25 per cent gas saturation are shown in Fig. 5 together with the relative permeability characteristics on the

Table II

Summary of Data for Floods in Which Static Gas Saturation Was Obtained by Oil Flood Followed by Pressure Reduction or by Internal Gas Drive

Run Number	7	8	9	10
Original Water Saturation, % Pore Vol	26.8	29.0	27.2	26.4
Original Oil Saturation, % Pore Vol	43.5	51.3	65.8	64.9
Original Gas Saturation, % Pore Vol. (Before Expansion)	26.1	14.4	5.3	0.
Original Gas Saturation, % Pore Vol. (After Expansion)	29.7	19.7	7.0	8.7
Final Water Saturation, % Pore Volume	54.5	60.2	63.0	64.1
Final Oil Saturation, % Pore Volume	16.7	22.4	29.8	28.8
Residual Oil, % Pore Volume (at 100 to 1 water-oil ratio)	18.2	23.1	29.8	29.0
Residual Oil, % Pore Volume* (at 100 to 1 water-oil ratio) (Before Expansion)	18.0	23.3	29.0	34.0
Final Gas Saturation, % Pore Volume (by dead oil replacement)	29.2	17.7	7.4	8.9

*This is the residual oil that previous data indicate would have been attained had the system been flooded under conditions before gas expansion.

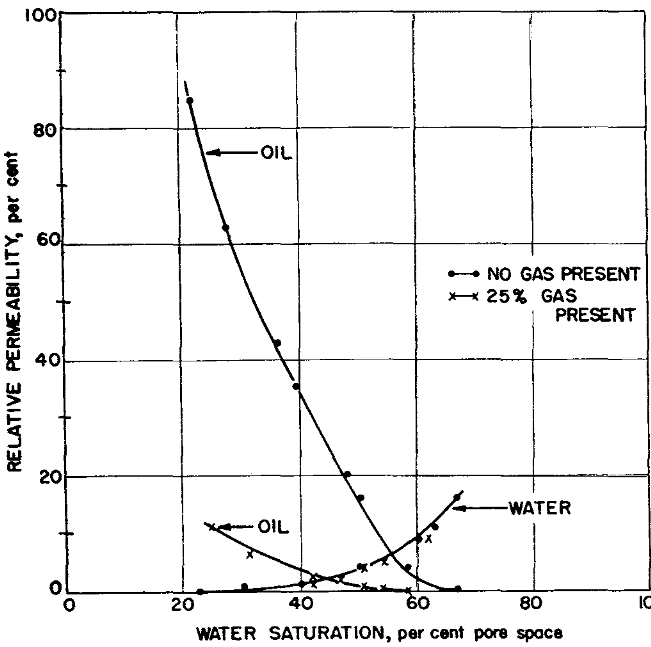

FIG. 5 — RELATIVE PERMEABILITY TO OIL AND WATER FOR TWO SYSTEMS IN NELLIE BLY SANDSTONE.

same system containing only oil and water. At any particular water saturation, oil relative permeability is drastically reduced when free gas is present, but water permeability is identical for the two conditions. A very important factor is that permeability to oil persists to much lower oil saturations with free gas present.

Fig. 6 is a plot of the construction necessary to compute the average water saturation at water breakthrough by the Buckley and Leverett frontal drive method with simplifications added by Pirson.[8] The calculations in this figure are for the reference run when no gas saturation was in the system. The computed average water saturation at water breakthrough is 65 per cent compared to the experimental value of 63.0 per cent. This difference can be attributed largely to dispersion of the flood front caused by capillary forces neglected in the simplified calculation. Fig. 7 shows the results of the same type computation for the system containing 25 per cent free gas saturation. The calculated average water saturation at breakthrough is 54.5 per cent; the experimentally obtained value, 53.2 per cent.

If the replacement of residual oil by gas had been in a 1:1 ratio, the reduction in residual oil would be equal to the gas saturation, or 25 per cent. Since a 1:1 ratio is not achieved, the reduction in residual oil at water breakthrough should equal the gas saturation less the difference in water saturations at breakthrough. From the computation of Figs. 5 and 6, this would be .25 − (.65 − .545) = .145 or 14.5 per cent. The difference obtained experimentally was 15.5 per cent. The close check between the experimental results and those calculated from appropriate relative permeability data leads to the conclusions that:

(1) The effects of free gas in water flooding are the alteration of oil relative permeability characteristics and the occupation of space which would otherwise be filled with residual oil.

(2) The reduction in residual oil which can be expected by the maintenance of free gas saturation during water flooding in a particular reservoir rock can be calculated from appropriate water-oil relative permeability characteristics.

The degree of improvement in oil recovery by water flooding which can be accomplished by maintenance of free gas saturation during the flood can be expected to vary widely between different reservoir materials. It would be gross speculation to attempt estimation of the benefits to be derived from a particular reservoir without measurements on cores from that reservoir.

PRACTICAL APPLICATION

It is obvious from the foregoing that maintenance of a maximum free gas saturation during water flooding can very substantially reduce residual oil saturation and hence increase oil recovery, providing it is feasible for application to a particular reservoir. Improved recovery of the magnitude indicated by the experimental work reported herein, could result in doubling the water flooding recovery from some semi-depleted fields. Of comparable importance in the water flooding of depleted reservoirs are the smaller volume of water required for fill-up, the earlier start of water flood production, and a more uniform oil producing rate.

One readily apparent means of accomplishing the maintenance of such a gas saturation is by gas injection to build up the reservoir pressure to such a level that the pressure differential across the oil bank will be a small fraction of the absolute pressure and thereby reduce compression of the gas present. A means of eliminating a large part of the loss of free gas due to solution in the oil is the injection of a gas of low solubility, such as nitrogen.

A very significant feature in the application of free gas saturation maintenance during water flooding is the reduction

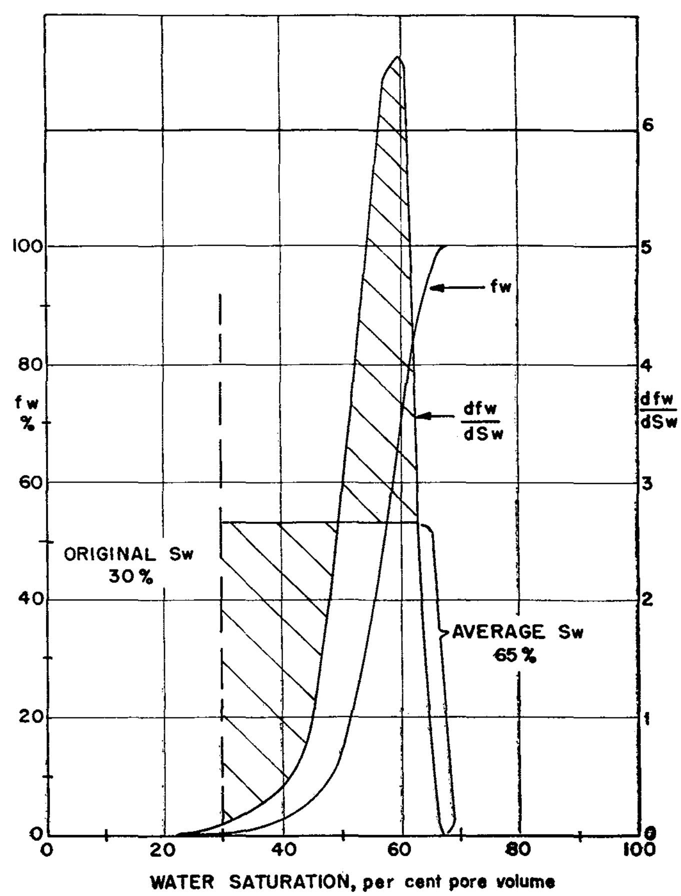

FIG. 6 — COMPUTATION BY FRONTAL DRIVE METHOD OF BREAKTHROUGH WATER SATURATION WITH NO GAS PRESENT.

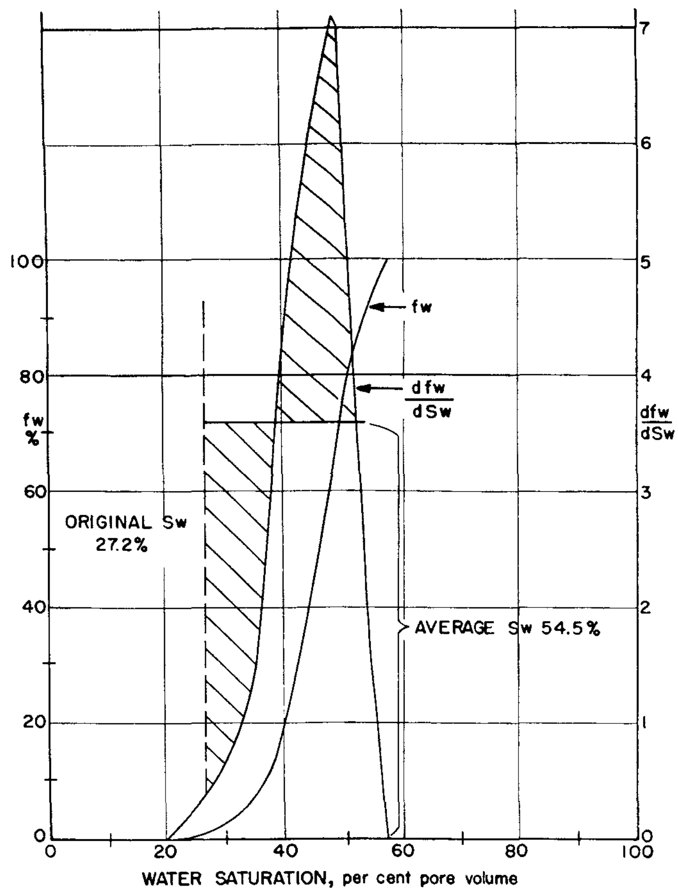

FIG. 7 — COMPUTATION BY FRONTAL DRIVE METHOD OF BREAKTHROUGH WATER SATURATION WITH 25 PER CENT GAS SATURATION PRESENT.

in capacity of producing wells. High gas saturation in the reservoir can reduce oil permeability to the order of magnitude of 1/10 the specific permeability as indicated by the relative permeability curves of Fig. 5. This permeability reduction will cause a reduction of the same magnitude in the productivity indices of the wells. Whether operations can be conducted at such reduced producing capacities may be of controlling importance in determining application to some fields.

Whether it will be economically feasible to reduce pressure in primary water drive fields to cause internal evolution of free gas ahead of the water flood front will be determined by a number of factors, such as

(1) The shrinkage of oil, resulting from pressure reduction necessary to obtain the gas saturation, compared to the expected decrease in ultimate oil saturation.

(2) Marked decreases in productivity indices of producing wells and hence an increased tendency for water coning.

(3) Variation in oil properties with structure. Some high relief reservoirs have much lower bubble point oil at the water-oil contact than further up structure. Under such conditions it would be almost impossible to obtain free gas at the water-oil contact without depletion by internal gas drive of the upstructure part of the field.

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REFERENCES

1. Schiffman, Louis, and Breston, J. N.: "The Effect of Gas on Recovery When Water Flooding Long Cores," *Producers Monthly* (January, 1950), **14,** No. 3.
2. Pfister, R. J.: "More Oil from Spent Water Drives by Intermittent Air or Gas Injection," *Producers Monthly* (September, 1947), **11,** No. 11.
3. Holmgren, C. R.: *Trans.* AIME (1949), **179,** 103.
4. Krutter, Harry, and Day, Robert J.: *J. of Pet. Tech.,* (Nov., 1943).
5. Dykstra, Herman, and Parsons, R. L.: "The Prediction of Oil Recovery by Water Flood." Paper presented at Spring Meeting of API, May, 1948.
6. Geffen, T. M., Owens, W. W., Parrish, D. R., and Morse, R. A.: *Trans.* AIME, (1951), **192,** 99, J. of Pet. Tech., (April, 1951).
7. Buckley, S. E., and Leverett, M. C.: *Trans.* AIME, (1942), **146,** 107.
8. Pirson, S. J.: *The Elements of Oil Reservoir Engineering,* McGraw-Hill Book Co., N. Y. C., (1950).

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