

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

Available from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22161.

NTIS price codes

Paper copy: \$7.00

Microfiche copy: \$3.50

CARBON DIOXIDE FOR THE RECOVERY OF CRUDE OIL

Annual Report
for the Period

November 1978—November 1979

T. M. Doscher, *Principal Investigator*
University of Southern California
Department of Petroleum Engineering
Los Angeles, California 90007
213/741-2066

R. L. Berg, *Technical Project Officer*
San Francisco Operations Office
Fossil Energy Division
1333 Broadway
Oakland, California 94612
415/273-7951

Work Performed for the U.S. Department of Energy
Under Contract No. EY-76-S-03-0113

Date Published—August 1980

U.S. DEPARTMENT OF ENERGY

TABLE OF CONTENTS

	<u>Page</u>
I. ABSTRACT	1
II. INTRODUCTION	3
III. RESIDUAL OIL SATURATION	5
IV. THE HYPOTHESIZED MECHANISM FOR THE DISPLACEMENT OF RESIDUAL OIL BY A MISCIBLE SOLVENT	7
V. THE EFFECT OF A VERY UNFAVORABLE VISCOSITY RATIO BETWEEN INJECTED SOLVENT AND WATER	13
VI. LOW VELOCITY PHENOMENA	15
VII. THE MIXING OF SOLVENT AND OIL BEHIND THE SATURATION JUMP	17
VIII. INFLUENCE OF CAPILLARY PRESSURE	19
IX. CONCLUSIONS	21
TABLE I - PERAMETERS FOR RUNS 9, 15, 17 and 42	25
REFERENCES	26
APPENDIX A - SCALING	29
TABLE I - LENGTH AND PERMEABILITY OF THE MODELS AND THE SCALED PROTOTYPE PERMEABILITIES	37
APPENDIX B - EXPERIMENTAL TECHNIQUES	38
FIGURE A-1	39
TABLE II - DENSITY AND VISCOSITY OF HEXANE, NONANE, AND DODECANE AT AMBIENT TEMPERATURE	45
FIGURES 1 - 11	49-59

I. ABSTRACT

The displacement of residual oil to waterflooding by miscible fluid injection has been studied using scaled physical models of line-drive systems. The effects of flow rate, mobility ratio, and density ratio, were investigated. This work was a first step in an overall program of studying miscible displacement in particular by carbon dioxide, of residual oil as a process for recovering additional crude oil from reservoirs which had been waterflooded.

It has been observed that to the extent to which these models have validity for the real world reservoir processes, recovery of crude oil in miscible tertiary recovery processes will occur if, and only if, moveable water is displaced ahead of the solvent.

In order to displace the water effectively, favorable solvent/water mobility ratios are required. When the viscosity ratio is only slightly unfavorable the efficiency of the process can be increased significantly by maintaining a high fluid velocity. A high fluid velocity can also compensate, to some extent, for the lower overall recovery observed when the solvent has a lower density than that of water.

At low velocities, the low density solvent showed a much earlier breakthrough and lower ultimate recovery of the residual oil. Override of low density solvents was visually confirmed by using colored solvents. Despite the earlier breakthrough and lower ultimate recovery observed in such systems, the solvent efficiency, volumes of oil recovered/volume of solvent injected, in the early life of the flood is significantly greater than when overriding is controlled by matching the density of the solvent to that of the water or employing higher velocities.

The ratios of gravitational and viscous forces which exist in tertiary recovery operations, using carbon dioxide as a recovery reagent, were approximated in a scaled physical model at ambient pressure and temperature. The viscosity ratio was now very unfavorable and displacement of moveable water was inefficient. Consequently, the displacement of the residual oil by the solvent, which was simulating the role of carbon dioxide, was also poor. The recovery efficiency could not be improved by reasonable increases in the fluid velocity because the unfavorable mobility-caused viscous fingering was so dominant.

Insomuch as carbon dioxide flooding, an imperfectly miscible recovery process, cannot be expected to perform as well as a perfectly miscible recovery process, these experiments point to the need for imposing a strong measure of mobility control if the injection of carbon dioxide is to achieve widespread usage for the recovery of residual oil.

II. INTRODUCTION

Project EY-76-S-03-0113, "Carbon Dioxide for the Recovery of Crude Oil" was activated at the University of Southern California in November 1978.* In November 1979, work was suspended and resumed again in February 1980.**

The research to be performed under the contract is described in the contract as follows:

1. Examine Phase changes that occur in dynamic systems.
2. Lateral diffusion of carbon dioxide.
3. Effects of additives on rendering CO₂ more viscous and dense.
4. Combine use of CO₂ with other reagents.

A functional interpretation of the foregoing might be restated as follows: The purpose of the research is to learn how the interaction of carbon dioxide with reservoir

* The effective date for contract initiation was June 1, 1978 but funding was unfortunately delayed.

** A funding hiatus occurred between November 1979 and February 1980.

crude oil and synergistic agents might overcome the deficiency of carbon dioxide as an enhanced recovery agent. The most over deficiency being its high mobility and propensity to finger or channel through the porous medium.

The two prongs of the research effort were to be (a) PVT studies of the carbon dioxide-crude oil-and additives systems, and (b) scaled physical model studies of the displacement of residual oil by carbon dioxide in linear systems.

Following the certification of funding, orders for the high pressure equipment were placed with delivery a year off in the future. The first year's work has been devoted to establishing a base of understanding of true miscible displacement of residual oil using hydrocarbon systems in scaled models. This work is reported herein.

The work on the high pressure systems has already been initiated. In an attempt to correlate static phase behavior with displacement efficiency and physical changes occurring under dynamic displacement conditions, a series of experimental studies have been initiated using dodecane (completely miscible with carbon dioxide), hexadecane (exhibiting a high solubility for carbon dioxide but with which it is not miscible), and a high gravity, paraffinic crude oil.

The early results have corroborated some of the findings reported herein for the mode of displacement of residual crude oil under conditions of complete miscibility.

III. RESIDUAL OIL SATURATION

Residual oil to a waterflood is the non-mobile oil remaining in the reservoir (or laboratory simulation) following termination of water injection. A true residual oil saturation at which the oil is absolutely immobile is obviously never achievable in field operations since the economic limit is reached well before such a degree of immobility can be achieved. There may be reason to believe the same is true for laboratory observations, where the ability to measure trivial oil quantities is limited by both technology and the time that can be devoted to such observations.

The theoretical concept of residual, immobile saturation is of course drawn from relative permeability measurements which reveal the existence of a non-mobile non-wetting phase saturation which may range from a few percent (for gas) to as much as 30 to 40% for oil.

The residual oil saturation is presumed to be trapped by the so-called capillary or adhesional forces that are developed between fluids and solid surfaces. If it is assumed that the internal surfaces of the porous medium are preferentially wetted by water, then the non-wetting saturation is trapped as a result of the snap-off

of threads of the non-wetting oil as they exist from interstitial constrictions.³ Once the snap-off occurs, the oil retracts into a spatial element of a greater cross-section and remains immobilized because of the inadequacy of the applied pressure gradient to cause deformation and extrusion through the downstream constriction. If it is presumed that the internal surfaces are preferentially wetted by the crude oil, then the residual saturation of the latter is the oil which adheres to the internal surfaces because of the very low free energy associated with such a configuration.

In either case, residual oil is that oil which has trivial mobility at termination of operations and requires significantly more than any achievable increase in applied pressure differential to cause its mobilization and eventual production.

IV. THE HYPOTHESIZED MECHANISM FOR THE DISPLACEMENT OF RESIDUAL OIL BY A MISCIBLE SOLVENT

Several investigators have experimentally addressed the question of displacing a residual oil saturation in laboratory systems^{4,5,6,7} but none chose to use scaled models for their frame of reference. One of the most recent references concluded that the residual oil tended to be shielded by the water⁴, and represented that if the oil saturation was sufficiently high (above residual) the oil would be completely displaced; and if a residual then displacement would be less than complete. The conclusion was tempered by the cited observation that the recovery of residual oil was slowly increasing at the termination of the experiment. (One could assume therefore that the residual would have been completely recovered in time.)

Another investigator⁵ did conclude that the recovery of residual oil by a flowing mixture of solvent and water would in time be complete as a result of diffusion. A similar conclusion that solvent injection would gradually recover trapped oil as a result of diffusion gradients had been reached earlier.⁶

The Buckley-Leverett analysis for the frontal displacement of oil by water under the conditions of diffuse

flow (no saturation gradients in a vertical plane) is one of the cornerstones of classical petroleum engineering courses.⁸ Starting with the concept of relative permeability, the definition of fractional flow, and the obvious fact that mass must be conserved in such simple flow systems, the Buckley-Leverett analysis provides a simple way of tracking the longitudinal movement of fluid saturations and discontinuities in a porous media.

For the displacement of oil by water from a system which contains connate water, Fig. 1, the proper use of the Buckley-Leverett analysis leads to the conclusion that the number of pore volumes of oil which will be produced prior to the breakthrough of water is the inverse of the slope of the line joining the connate water saturation to the point of tangency. Following this bank of oil, water and oil are produced at a flowing ratio given by the ordinate of the point of tangency. Gradually, thereafter, the water saturation increases, in accord with the dictates of the fractional flow curve.

In the considerations that have been given such analyses in the past, no great interest was attached to the matter of what happened to the connate water originally present in the system; whether or not it was produced ahead of, or along with the injected water, or not at all.

The Buckley-Leverett analysis, being merely the simultaneous solution of the law of the conservation of

mass and the fractional flow equation is equally applicable to the displacement of water by a non-wetting phase as it is for its conventional use for the displacement of oil by water.

Thus, Figure 2, which is Figure 1 rotated through 180° , and the new tangent line represents the physical system for a solvent being injected into a porous media containing residual oil. (For simplicity, the viscosity of the oil and the solvent are assumed to be the same.) The course of the displacement must be as follows: Pure water is produced for $(1/S)$ pore volumes where S is the slope of the tangent line, and is then followed by a mixture of solvent and water containing W percent water in the effluent fluid. Continued flooding results in a continuously decreasing water content, following along the fractional flow curve from B to CW. The Buckley-Leverett analysis does not speak to the question of what happens to the residual oil since the latter was assumed to be non-mobile and therefore neglected in the solution of the appropriate fractional flow and mass balance equations.

To show the validity of this analysis, Figure 3 presents the very typical results for the displacement in a scaled physical model (see Appendix) of a reservoir which had been flooded to a residual oil (dodecane) saturation and then by a solvent (nonane) which is truly miscible with the oil. At reservoir prototype velocities above 0.1 foot

a day, and at water/solvent viscosity ratios of 0.5 to 2.0, and water/solvent density ratios of 0.1 to 1.3, the results of Figure 3 are typical of over 24 runs made in our laboratories.

The noteworthy feature of the displacement is this: an amount of water virtually equal to the [saturation of water following the waterflood less the connate water] is displaced ahead of the first appearance of non-wetting phase (solvent and/or oil). There is no necessary implication here that the connate water is different than the water saturating the system; the results merely show that water (the connate value) is again trapped by the invading solvent.

The residual oil appears to be "leached out" of the porous media by the subsequent injection and production of solvent following breakthrough of the latter. The recovery of oil is virtually 100% as a result of convective dispersion of solvent and residual oil into each other.

Molecular diffusion is explicitly scaled to physical length and height of the reservoir in the model, and it becomes apparent that the molecular diffusion in the model during the duration of these experiments (an hour or two at the most) could not have resulted in fluid migration across a significant fraction of the height of the reservoir, 2.5 inches. Because the scaling is explicit, the conclusion can be drawn that molecular diffusion would be equally

ineffective in the prototype reservoir.

It is relatively easy then to construct a phenomenological description of the manner in which a truly miscible solvent will recover residual oil from a reservoir which has been waterflooded. The solvent first displaces the water that separates globules, ganglia, films, or any other geometric configuration of isolated, immobile volumes of residual oil. In back of the Buckley-Leverett jump saturation the solvent, now occupying the entire cross-section except for the trapped water and the erstwhile trapped oil, is now capable of contacting the latter and mobilizing it.

The recovery of the residual oil is not an efficient process since it does require greater quantities of solvent to be injected than merely that required to displace the water. The displacement of the water could conceivably be done by a slug of solvent which retains its integrity during its course through the system. However, the residual oil does not instantaneously mix with the solvent at the saturation jump, and an additional supply of solvent is required to complete the mobilization even at a favorable solvent/water viscosity (see Fig. 8).

The foregoing represents an ideal (not idealized) situation where the so-called visous forces (imposed by the pressure gradient in the longitudinal direction) is sufficiently higher than the so-called gravity forces (the

pressure gradient that develops in the transverse direction as a result of density differences) so that diffuse flow is maintained across the cross-section of the reservoir. The experiments reported so far are limited to a ratio of the viscosity of solvent to water within less than a factor of two.

It must be noted that although these calculations are considered to be quantitatively sound with respect to the displacement of the water they are only qualitative with respect to the exact ratio of solvent to oil in the produced fluids subsequent to solvent breakthrough. The reason for this is the inability to scale the convective mixing in the laboratory model exactly to the convective mixing that will occur in the reservoir. This shortcoming, not as great as might be expected, will be discussed later.

V. THE EFFECT OF A VERY UNFAVORABLE VISCOSITY RATIO
BETWEEN INJECTED SOLVENT AND WATER

It is to be noted, if not already obvious, that the important ratios of fluid parameters are those between the solvent and the water that saturates the porous medium following the waterflood. The ratios between the parameters of the solvent and oil do not influence the breakthrough performance of the solvent, but do appear to have an effect on the recovery of the residual crude oil following breakthrough, see VI.

Using the scaling rules described in the Appendix it was possible, by increasing the viscosity of both the water and the oil in the model (maintaining the same approximate unit ratio that characterizes the initial waterflood) and then using hexane as solvent, to obtain a viscosity ratio of solvent to water approaching that which might be expected in the displacement of a low viscosity residual oil by carbon dioxide, viz., 0.06, see Table I.

Again, at velocities above 0.1 foot per day, the results obtained were reproducible and characterized by those shown by Figure 4. Comparing this to the results obtained in Experiment 17 at a higher viscosity ratio of 0.33, it is seen that the breakthrough is much earlier in

the unfavorable viscosity ratio experiment. The recovery of residual oil occurs much more slowly, but still appears to be headed for virtual complete recovery. The efficiency of the recovery of residual oil by a low viscosity solvent is obviously seriously reduced, Figure 5.

The significant difference between the breakthrough volumes is completely in accord with the Buckley-Leverett analysis. Figure 6 shows the difference in the slopes of the lines, whose inverse values define the breakthrough pore volume for the system, for systems having unfavorable and favorable solvent/water viscosity ratios. The behavior of the low viscosity solvent is of course frequently referred to as being the result of viscous fingering. It is in fact a quantitatively definable phenomenon in terms of diffuse flow and the requirement that the system is controlled by the law of the conservation of mass.

The slower recovery of oil is to be associated with the fact that the water is produced at a lower rate. The presence of the water inhibits the contact of solvent with residual oil, and the mobilization of the latter is consequently slowed.

VI. LOW VELOCITY PHENOMENA

The preceding experiments were conducted at prototype velocities above 0.1 foot per day, which corresponds to the lower limits of fluid velocities that are usually anticipated in reservoir operations. Higher velocities had virtually no effect on the results.

Lower velocities however for the systems studied had pronounced effects. Apparently in these prototypes having a permeability of about 100 mds., the pressure gradient due to density differences began to compete with the gradient due to the imposed injection pressure at these low velocities (low imposed pressure gradients). Gravity overlay occurred. Run 15 at a prototype velocity of 0.018 feet per day is compared to Run 9 at a velocity of 0.26 feet per day in Figure 7 (see Table I for other details).

The production of water at the lower rate was delayed by an early breakthrough of solvent. However, an unexpected result occurs; initial production of oil per volume of solvent injected is significantly greater than at higher rates, see Figure 8. A significant fraction of the early recovery is obtained as neat oil. Eventually the ratio of recovered oil to injected solvent for the low

rate operation decreases well below that of the one at a higher injection rate.

The existence of the gravity override was confirmed by adding a colored dye to the solvent so its course of flow could be visually observed. The reason for some neat oil production (a higher ratio of oil to solvent in the produced fluids in general) can only be surmised at this time: Because the greater retention time in the system, see Fig. 9, the effect of molecular diffusion is now capable of making a significant contribution to the mixing of the solvent and the residual oil.

Although this more efficient production of residual oil in terms of solvent injected suggests an economic advantage of these low rates, it is obvious when Fig. 9 is studied that the significantly greater time required for the recovery would economically negate that advantage.

Increasing the prototype permeability increased the gravity overlay at any given longitudinal velocity as would be expected as a result of the lowered ratio of viscous to gravity forces.

VII. THE MIXING OF SOLVENT AND OIL BEHIND
THE SATURATION JUMP

The experiments reported herein have given some insight into a recovery parameter, defined as the fraction of residual oil recovered at 1.4 pore volumes of injected solvent. Figure 10 shows the trend of this recovery parameter for a series of runs in which the viscosity of the residual crude oil was increased and that of the solvent remained constant. As might have been expected, the recovery parameter decreases with increasing viscosity of the residual crude.

The absolute values of these recovery parameters are not to be taken to be significant at this time. The models that were used explicitly scaled molecular diffusion, gravitation and imposed pressure gradients. They did not scale the local dispersion due to particle size and tortuosity. These effects will be sensed in the post-solvent-breakthrough recovery of oil.

Convective mixing has been shown by Pozzi and Blackwell to be increased by velocity and decreased by particle size.⁹ Since in these scaled models the fluid velocities are several hundred times those of the reservoir prototype the effect of velocity will have been to increase

the dispersion significantly. On the other hand, the particle size is much greater in our model experiments, and if a classical relationship between particle size and permeability is used the particle size has been increased by the square root of the ratio of the model permeability to the prototype permeability. Therefore, dispersion has been reduced in proportion to the square root of the velocity (scaled as permeability). Thus, as a first approximation dispersion has been increased in the model by the square root of the ratio of model permeability to prototype permeability, or a factor of 20. Thus, the recovery of crude oil by solvent at first blush would appear to be very optimistic in these studies. However, further work must be done on this subject to quantify the recovery of residual crude oil after solvent breakthrough. It may only be possible to do so by correlating actual field operations.

VIII. INFLUENCE OF CAPILLARY PRESSURE

Scaling the diffusion, imposed pressure gradient, and density differences prohibits proper scaling of the capillary pressure in our models. It is believed that the effect of capillary pressure is sensed in its effects on the relative permeability curves, and therefore on the fractional flow curve. To the extent that the fractional flow relationship is different in a real reservoir and the prototype of our model, the exact value of solvent injection resulting in breakthrough of solvent will be different. Phenomenologically, the displacement process will not be altered.

Another aspect of the difference between a real reservoir and the prototype for our model could be thought to be in the differences in the end point, or residual saturations, which are components of the relative permeability and hence of the fractional flow curves. In most of the experiments described herein the residual saturations of oil ranged between 20 and 30% p.v.: the same range that is usually associated with field operations. Only in one instance, when simulating the displacement at very unfavorable viscosity ratios, e.g., Run 42 was the residual oil saturation significantly different, viz., 12%. (This was

due to having to use a very high permeability for the model in order to achieve the desired scaling.) It is therefore precluded, when comparing Run 42, with Run 17, to make conclusions concerning the significance of differences in absolute recovery of residual oil. The proper comparison of course is the percentage recovery of residual, as already noted. It is not likely that the differences in residual oil saturation would significantly affect the solvent breakthrough. If anything, a shift in the end point saturations to lower values would result in a lower value of the slope of the Buckley-Leverett tangent line, and a delayed breakthrough which is opposite to what was actually observed due to the decreased solvent/water viscosity ratio.

IX. CONCLUSIONS

Experiments reported in this study using physical models explicitly scaled for diffusion, imposed pressure gradients, and density differences between oil, water and solvent gave consistent and reproducible results.

1. The experimental works reported herein confirm that the Buckley-Leverett analysis is applicable for estimating the production history resulting from the injection of a solvent into a waterflooded reservoir as long as diffuse flow is maintained.
2. The injection of a solvent for the recovery of residual oil under at anticipated injection rates will therefore first result in the production of water prior to the production of any solvent and residual oil.
3. The amount of water produced will be a function of the viscous ratio of the solvent to the water; the lower this ratio the less the water produced.
4. Accompanying the breakthrough of solvent, oil will be produced in solution in the solvent. Eventually, all the oil will be recovered.

5. The speed at which the oil is recovered will be a function of the completeness with which the water has been displaced and produced. At high solvent/water mobility ratios virtually all the mobile water (total less the connate quantity) is produced ahead of the solvent breakthrough and the subsequent recovery of residual oil is then complete with the injection of an additional pore volume of solvent in these experiments. When the solvent/water mobility ratio is poor, much larger injection volumes of solvent are required to complete the recovery of residual oil.
6. The recovery of residual oil by solvent behind the saturation jump, dictated by the Buckley-Leverett analysis, is primarily due to convection mixing resulting from the fluid velocities and the tortuosity of the porous medium.
7. The results for recovery reported herein are not quantitative because the internal lithology of the porous medium was not scaled. However, rational arguments suggest that the scaling for other factors resulted in optimistic results.
8. By extrapolation, mobility control in real-world solvent flooding will result in an increase in efficiency of recovery of the residual crude oil

in terms of pore volumes of solvent injected, but may be economically negated by the greater time required. The efficiency of mobility control agents will still be limited by the prior production of all the mobile water and convective mixing behind the saturation jump. A small slug of solvent will not be adequate since it will not provide a long enough mixing zone behind the solvent front.

9. The foregoing are valid for diffuse flow in a single layer. Obviously, very thick layers and multiple layers which will permit gravity segregation and unequal entry into individual layers will sorely reduce the implied efficiencies based on the experiments reported herein.
10. The future course of work on this subject will be aimed at the validation of the conclusions drawn from the completed work. Two series of experiments will be undertaken:
 - (1) Scaled linear models using carbon dioxide as the solvent and reconstituted crude oil at high pressures comparable to those anticipated in reservoir operations. Correlative phase studies of the crude oils used in these experiments and carbon dioxide and the diffusion of carbon dioxide through water will also be studied.

These factors and the results of the displacement runs will be studied for further elaborating the mechanism and efficiency of displacement of residual oil by carbon dioxide.

(2) Three-dimensional physically scaled models, with one and several parallel layers, using continuous, slug, and WAG injection will be undertaken to seek out modifications to these conclusions due to radial geometry and vertical heterogeneity.

11. Carbon dioxide recovery of residual crude oil after waterflooding is not as promising as originally anticipated because of the required displacement of the mobile water ahead of the solvent, and the observation that the residual oil is not banked up ahead of the solvent but is leached out of the porous media. Obviously, carbon dioxide will be a significantly more efficient recovery agent if applied to the reservoir while the oil is still at a high, mobile saturation.

Table I

PARAMETER FOR RUNS 9, 15, 17 and 42
(12 Length x 2.5" Diameter)

Solvent/ Oil	Run No.	$\frac{\mu_o}{\mu_s}$	$\frac{\mu_w}{\mu_s}$	$\frac{\rho_o}{\rho_s}$	$\frac{\rho_w}{\rho_s}$	Prototype Velocity (ft/day)	Prototype Permeability (md)	Porosity (%)	S_{oi}	S_{or} (Water- flood)	S_{wit}	% FORO @ 1.4 pv
Ca/C ₁₂	9	1.9	1.4	1.04	1.4	0.264	105		0.796	0.19	0.81	96
Ca/C ₁₂	15	1.9	1.4	1.04	1.4	0.0176	105		0.84	0.26	0.74	60
C ₆ /C ₁₂	17	4.1	3.0	1.13	1.51	0.264	105	37.3	0.80	0.234	0.766	84
C ₆ /Mineral Oil	42	22.4	16.7	1.2	1.6	0.264	105	37.3	0.81	0.12	0.88	62.3

REFERENCES

1. Doscher et al., "Carbon Dioxide for the Recovery of Crude Oil", Department of Petroleum Engineering, University of Southern California (June 30, 1979).
2. Doscher, T., and Kuuskraa, V., "Carbon Dioxide for the Recovery of Crude Oil", SPE Regional Meeting, Ventura, California, April 1979.
3. Roof, J. G., "Snap-Off of Oil Droplets in Water Wet Pores", SPEJ., vol. 10(1), 85 (March 1970).
4. Shelton, J. O., and Schneider, F. N., "The Effects of Water Injection on Miscible Flooding Methods Using Hydrocarbons and Carbon Dioxide", SPEJ, v. 15(3), 217 (June 1975).
5. Stalkup, F. I., "Displacement of Oil by Solvent at High Water Saturation", SPEJ., vol. 10(6), 337 (December 1970).
6. Raimondi, P., Torcaso, M. A., and Henderson, J., "The Effect of Interstitial Water of the Mixing of Hydrocarbons During a Miscible Displacement Process: Mineral Industries Experimental Station Circulation No. 61, Pennsylvania State U., (October 1961).

7. Raimondi, P., and Torcaso, M., "Distribution of the Oil Phase Obtained Upon Inhibition of Water", SPEJ., vol. 3(3), 189 (September 1963).
8. Dake, L. P., Fundamentals of Reservoir Engineering, Chapter 10, Elsevier, New York, 1978.
9. Pozzi, A. L., Jr., and Blackwell, R. J., "Design of Laboratory Models for the Study of Miscible Displacement", SPEJ., vol. 3(3), (March 1963).
10. Vennard, J. K., Elementary Fluid Mechanics, John Wiley and Sons, New York (1966), 267-274.
11. Lenerett, M. C., Lewis, W. B., and True, M. E., "Dimensional-model Studies of Oil-Field Behavior", Trans., AIME (1942) 146, 175.
12. Engelberts, W. F., and Klinkenberg, L. J., "Laboratory Experiments on the Displacement of Oil by Water from Packs of Granular Material", Proceedings Third World Petroleum Congress, The Hague (1951) Section II, 544.
13. Rapoport, L. A., and Leas, W. J., "Properties of Linear Waterfloods", Trans., AIME (1953) 139, 198.
14. Offeringa, J., and van der Poel, C., "Displacement of Oil from Porous Media by Miscible Liquids", Trans., AIME (1954) 201, 310.

15. Geerstma, J., Croes, G. A., and Schwartz, N., "Theory of Dimensionally Scaled Physical Models", Trans., AIME (1956) 118, 207.
16. Pozzi, A. L., Jr., and Blackwell, R. J., "Design of Laboratory Models for the Study of Miscible Displacement", SPEJ., (March 1963).
17. Muskat, M., The Flow of Homogeneous Fluids Through Porous Media, J. W. Edwards, Inc., Ann Arbor, Michigan, 1946.
18. Ettre, L. S., Basic Relationships of Gas Chromatography, Perkin-Elmer (1977).

APPENDIX A

SCALING

Physical scaling has long been recognized to be an effective tool for studying the performance of a prototype operation. Scaling has been used for aerodynamics and hydrodynamic studies as well as petroleum reservoir performance for studying the analytically undefinable characteristics of the processes. Scaling is not justified where tractable analytical methods yield a reliable solution.

Scaling is based on dimensional analysis^{10,11,12} and/or inspectional analysis.¹³ Dimensional analysis is the combination of variables into dimensionless groups that characterize the process under study. In dimensional analysis, therefore, a thorough knowledge of the complete set of relevant variables is essential. In inspectional analysis, however, the dimensional homogeneity of the equations describing the behavior of the system to be studied is used.

Offeringa et al.¹⁴ constructed scaled models to study solvent displacement based only on inspectional analysis, while Geerstma¹⁵ laid out the scaling requirements for solvent displacement studies by a combination

Physical Scaling of the Miscible
Displacement Process

The basic principle of physical scaling for a reservoir process requires that the ratio of all the dominant forces acting to control the behavior of the prototype, e.g., viscous forces to gravitational forces, have the same value in the laboratory model as they do in the prototype. For scaling the solvent injection process, inspectional and dimensional analysis indicate the following equalities must be maintained.^{1,8}

$$\frac{\left(\frac{k\Delta\rho}{v\mu}\right)_P}{\left(\frac{k\Delta\rho}{v\mu}\right)_P} = \frac{\left(\frac{D_m}{v\ell}\right)_P}{\left(\frac{D_m}{v\ell}\right)_M} = \frac{\left(\frac{v\rho\sqrt{k}}{\mu}\right)_P}{\left(\frac{v\rho\sqrt{k}}{\mu}\right)_M} = \frac{\left(\frac{\ell}{\sqrt{k}}\right)_P}{\left(\frac{\ell}{\sqrt{k}}\right)_M}$$
$$= \frac{\left(\frac{kp_c}{v\mu\bar{\ell}}\right)_P}{\left(\frac{kp_c}{v\mu\bar{\ell}}\right)_M} = 1$$

There is no problem in constructing an experiment in which the first ratio that of gravity to viscous forces is set equal to one: By using the prototype fluids in the laboratory model it is only necessary to adjust the permeability and fluid velocity to convenient values as long as their ratio is kept constant. Since it is this ratio, more than any other, that affects the breakthrough of the injected fluid it is fortunate that it is so readily scaled.

The second term scales the molecular diffusion to the viscous forces and again, by using the same fluids in the model, it is readily included in the scaling along with the first term. The combination of the two yields the following conditions for the experiment:

$$\gamma(k) = \gamma(v) = \gamma(l^{-1})$$

The third scaling ratio is that for the Reynold's number. Since in the prototype and the laboratory model the Reynold's number will be in the laminar flow regime it is not considered necessary to maintain appropriate scaling for this dimensionless number.

The fourth scaling ratio is that for the ratio of the total length of the system to the number of pores per unit length of the system, essentially a scaling factor for the particle size distribution, in which the root of the permeability has been substituted for particle diameter.

If this ratio was maintained at a value of unity it would be impossible to maintain the proper scaling of the important ratio of gravity to viscous forces. It has been concluded that the latter is far more important and therefore the fourth term is neglected. The result of this is that, since its neglect results in using a larger particle size than is called for, is a diminution in the effect of convective mixing, due to particle size or tortuosity, in the model. Since the model velocities as a result of scaling of the gravity/viscous ratio are higher than in the prototype convective mixing will be enhanced because of this. Experimental work reported in the literature³ indicates that the effect on convective mixing varies in proportion to a higher power of velocity than to the power dependence of the inverse of the grain size. Hence, the net result of neglecting this scaling ratio is to enhance convective mixing in the laboratory model.

The last scaling ratio is that of capillary forces to viscous forces. It is a difficult term to scale since there is no a priori knowledge of the value of the \bar{l} , the effective length of the residual oil volumes that are trapped by the waterflood. Frequently, \bar{l} is assumed to be a direct function of the grain size, and substituting the root of permeability for the grain size leads to the dimensionless capillary term of $(\sigma/v\mu)$. This is probably incorrect, in general, since the smaller the pore throat

and the higher the capillary pressure the larger will be the length of the residual oil volume over which a given pressure gradient is inadequate to eject the oil. If $\bar{\ell}$ is assumed to be an inverse function of grain size then the capillary/viscous ratio would become $(k\sigma/c_{\ell}v\mu)$. Using the same fluids would result in the ratio being scaled as long as the gravity to viscous ratio was scaled.

Should grain size and the length of the residual oil volume be proportional to each other, then the assumption of the preceding paragraph will result in the capillary pressure of the model being too low for proper scaling because of the much larger grain size used in scaling the gravity to viscous ratio. Thus, any shielding of the residual oil by capillary forces during the solvent flood will be minimized and the results will be too optimistic on this account.

It should be noted in summary that those scaling factors about which there is some equivocation are those which affect the subsequent recovery of residual oil after breakthrough of the solvent and not the phenomena occurring at the solvent water interface(s), viz., frontal displacement, gravity override and viscous fingering.

The foregoing discussion leads to the following residual scaling groups:

$$F(D) = F(v) = F(\ell^{-1}) - F \frac{\Delta\rho k}{\mu} = F(h^{-1})$$

When using the same fluids (density ratio, viscosity and diffusion coefficients are identical in model), then:

$$F(D) = F(\Delta\rho) = F(\mu) = 1$$

and

$$F(v) = F(k) = F(\ell^{-1}) = F(h^{-1})$$

[F = dimensionless scaling factor]

Three different 10 acre line drive prototypes, with an injector/producer spacing of 467 feet, and absolute permeabilities of 29, 105 and 573 millidarcies were used (Table I). With some slight modification in the model a prototype for a very adverse viscosity ratio (e.g., miscible carbon dioxide tertiary oil recovery) was studied.

In constructing these models, it was assumed that reservoirs were homogeneous and fluid distribution to waterflooding was uniform. The tests were conducted with a solvent-oil pair that was miscible upon first contact at atmospheric pressure and ambient temperature (e.g., C₉ and C₁₂).

In scaling a 10-acre line drive prototype operation when the interwell spacing is 467 feet the scaling factor is 448 if the model length is chosen to be 12.5 inches. The diameter of the pack was 2.5 inches, corresponding to 93.4 feet net pay thickness in the prototype. The first

requirement: $\left(\frac{\ell}{h}\right)_M = \left(\frac{\ell}{h}\right)_P$ is therefore satisfied.

According to the final residual scaling groups prototype permeability has to increase by a factor of 448 (scaling factor) in the model to meet the scaling requirement. Because this study was not conducted for a specific prototype the model permeability was preset by specific glass beads and the permeability of the hypothetical prototype was back calculated using the scaling factor (e.g., $k_M = 47$ darcies, $k_P = 105$ millidarcies, $k_M/k_P = 448$).

The rate of solvent injection in the prototype was also back calculated knowing the limits of solvent injection in the laboratory (within the laminar region). Note that the velocity and the rate of the solvent injection vary inversely from prototype to model. In other words, the velocity is increased by the scaling factor while the rate of solvent injection is decreased by the scaling factor for the laboratory model.

Table I

LENGTH AND PERMEABILITY OF THE MODELS AND THE
SCALED PROTOTYPE PERMEABILITIES

Model No.	Model Length (inches)	Model Permeability (darcy)	Permeability
G.B.P. 1a*	12.5	47	0.105
G.B.P. 1b	12.5	13	0.290
G.B.P. 1c	12.5	257	0.573
G.B.P. 2	25	47	0.105

* G.B.P.: Glass Bead Pack

APPENDIX B

EXPERIMENTAL TECHNIQUES

A. Experimental Apparatus

Schematic representation of the test apparatus is indicated in Figure A-1. The apparatus consists of a fluid reservoir, pumps, pulse preventor, pressure gauges, glass bead pack, back pressure regulator, effluent collector and analytical instruments such as a refractometer and a chromatograph. A brief explanation in regard to each part is given as follows:

1. Fluid Reservoir: A large 1,000 cc burett with teflon valve was used. If the required amount of injected fluids were in excess of 1,000 ccs., the burett was refilled. The accuracy of the input was correlated against the total incremental output.

2. Pump: Two Cole-Palmer tubing pumps were used with different ranges of discharge rates. Even though each pump had several turbine heads for different discharge rates, addition of the second pump made the operations more versatile and expeditious. There were slight differences in the range of rates of discharge for each

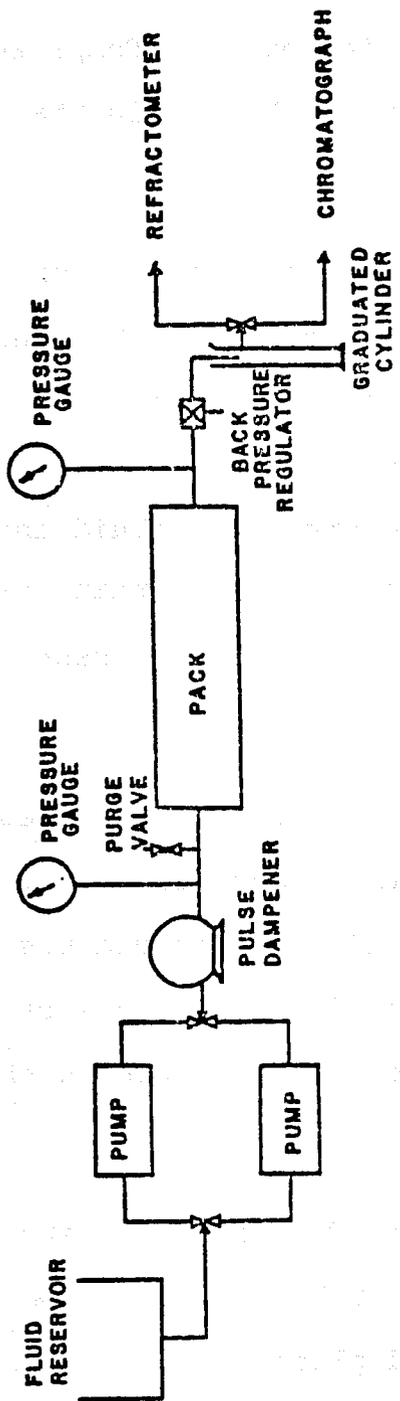


Figure A-1

tubing head in two injection pumps. Pumps were calibrated in the factory and also recalibrated in the laboratory as necessary.

3. Pulse Preventer: The discharge of fluids from the Cole-Palmer pumps was accompanied by a noticeable pulsation. A chamber of approximately 300 cc. was used as a pulsation dampener to establish a constant and steady flow rate which then discharged the fluid into the glass bead pack. The flow stabilization within the chamber was obtained by applying a constant air pressure on top of the liquid all the time.

4. Pressure Gauge: Two pressure gauges were used; one at the beginning of the glass bead pack, the other one at the end. Even though all the experiments were conducted at close to atmospheric conditions, pressure gauges were sensitive enough to indicate any problem within the experimental group.

5. Glass Bead Pack: Two equal diameter plexi-glass cylinders, but of different length ($2 L_1 = L_2$) used with specially constructed end plates. Both had a diameter of 2.5 inches and lengths of 12.5 and 25 inches. Our standard runs were performed in the small ($L = 12.5$ inch) cylindrical pack. Three different glass bead sizes were used to obtain the scaled permeabilities.

End plates were constructed in such a way that the initial velocity at the inlet boundary was constant over the entire cross-section. This was done through creation of a small volume on the end plate. This dead volume was located over the entire cross-section between the end plate itself and two screens in the end plate. The screens were placed on the end plate in such a manner that the inner screen (closest to the pack) was a finer screen to prevent glass bead flow (very fine glass beads, 0.17 - 0.18 mm., were used) and the second screen was a coarse screen to keep the inner screen stable. This operation was very delicate and had to be done with great care. A vent valve was located at the top of the end plate to vent any air that may have been trapped on initial saturation of the system. The experiment was stopped if any air accumulated in the end plate volumes. (This would have endangered the constant velocity formation across the cross-section of the pack and subsequently the accuracy of total liquid pore volume).

6. Back Pressure Regulator: Since the experiments were performed horizontally and the pack diameter was large, a small back pressure was used to assure the complete saturation at the outlet boundary of the pack.

7. Effluent Collector: Graduated cylinders in different sizes were used.

8. Refractometer: A refractometer was used to measure the refractive indices of the unknown samples and back calculate the percent of different fluids present in the unknown. The unknowns oil and solvent and their percentage was obtained from an early calibrated line. The refractometer was a four-decimal refractometer and was operated at a constant temperature of 25°C.

9. Chromatograph: Chromatograph was also used for analysis of unknown samples. A gas chromatograph, Perkin-Elmer Type GC4, with an integrator and a chromatograph were used. The gas chromatograph was able to analyze liquid hydrocarbons up to a range of C₁₈ or C₂₀. The liquid hydrocarbon was vaporized upon injection into the chromatograph (T = 250°C) and helium gas carried the unknown sample through the column at a constant temperature of 200°C (the maximum applicable temperature on the column was 250°C). The detector was a Flame Ionization Detector (FID) and hydrogen and air were used for the purpose of burning and quantizing the amount of each component in the unknown sample. Quantization was achieved and recorded by the integrator and the occurrences of every component was checked with the chromatogram.

The retention time¹⁸ of pure components were determined and the system was calibrated with the known quantities (percent volume) of the samples.

Calibration was performed and calculated by normalization with Relative Response Factors. The primary advantage of this technique is that with the same detector conditions, the relative response factors will not change. It was not necessary to have reproducible detector sensitivities as in the direct or absolute calibration technique and calibration curves need not be obtained as frequently. The major drawback to this method was that it assumed that all peaks had been detected and calibrated. After calibrating for a relative response factor and knowing the actual value for RRF, calculation of actual concentration value (in percentage) from peak areas of unknowns were made possible. This was done by correcting the area of the unknown to the standard with the relative response factor to get "corrected area," then dividing the corrected area for each component by the total corrected area. Retention times and raw areas were produced directly by the integrator.

Hexane (C₆)*, Nonane (C₉)*, Dodecane (C₁₂)*, and white mineral oil were used. For the cases of thick and more viscous water requirements, polyethylene glycol was added into the deaerated water. Component composition analysis for hydrocarbons was performed by chromatograph and mineral oil by refractometer.

*Phillips pure grade.

B. Procedure

To perform a displacement experiment, the following steps were taken:

1. The cylindrical lucite pack was filled with glass beads and vibrated with an electrical vibrator to insure a minimum number of permeability inhomogeneities.

2. The pack was positioned vertically and saturated with deaerated water. The deaerated water was pumped at a very low rate from the bottom end of the pack.

3. The pack was laid horizontally with the top end now attached to a pressure gauge through which it was connected to a back-pressure regulator. Care was taken to insure a complete liquid filled space within the dead end volumes located at both ends of the pack.

4. The oil was charged into the pack to displace water and subsequently to develop a high oil saturation and an irreducible water saturation.

5. The oil was then displaced by water to reduce the initial reservoir oil saturation to the residual oil saturation. Water cuts were carefully examined, and not until the WOR reached 200 was injection terminated.

6. At this time solvent was injected at controlled rates of injection to displace the residual oil. Rates of oil input and rates of waterflooding were kept constant for all of the experiments to secure reproducible conditons. All the experiments were performed at atmospheric pressure and ambient temperature.

Five different types of solvent-oil systems were used:

1. A high molecular weight hydrocarbon such as dodecane was displaced by low molecular weight hydrocarbons such as hexane in the presence of continuous deaerated water phase. The visocosity ratio in terms of both solvent-oil and solvent-water were unfavorable. Table II shows that there is a larger density difference in solvent-water than in solvent-oil.

Table II

DENSITY AND VISCOSITY OF HEXANE, NONANE,
AND DODECANE AT AMBIENT TEMPERATURE

Oil Type	Density (g/cc)	Viscosity (cp)
Hexane	0.66	0.33
Nonane	0.72	0.71
Dodecane	0.75	1.35

2. A hydrocarbon such as dodecane was displaced by another hydrocarbon such as nonane. The viscosity ratio here, in both solvent-oil and solvent-water were unfavorable. Density differences were very small for the solvent-oil pair, while still it was considerable for the solvent-water pair. This system was used for three different scaled permeability models for application to different field reservoirs.

3. A hydrocarbon such as nonane was displaced by another hydrocarbon such as dodecane in tertiary flooding. The viscosity ratios in terms of both solvent-oil and solvent-water were favorable. There is some difference in density between solvent and water while there is almost none between solvent and oil.

4. A low viscosity solvent displaced one of higher viscosity hydrocarbon such as dodecane. The viscosity ratios in terms of both solvent-oil and solvent-water were poor. However, the density of solvent was matched to that of the water.

5. A low viscosity solvent (but having a higher viscosity than in (4)) displaced a hydrocarbon such as dodecane. The viscosity ratio in terms of both solvent-oil and solvent-water were unfavorable. The density of the solvent was tried to match that of the water.

Three basic types of displacement were studied:

1. All of the above-mentioned tests were conducted with regular deaerated water.

2. A diluted mineral oil was displaced by a hydrocarbon such as hexane in the presence of thickened, deaerated water (polyethylene glycol and deaerated water, $\mu_w = 5.5$ cp). The viscosity ratio in terms of both solvent-water and solvent-oil were poor. The density difference was small for solvent-oil pair while it was noticeable for solvent-water.

3. A hydrocarbon such as dodecane was displaced by a hydrocarbon such as hexane in the presence of thickened water ($\mu_w = 5.5$ cp) subsequent to waterflooding. The viscosity ratio in terms of both solvent-water and solvent-oil were poor. The density difference is larger in solvent-water than in solvent-oil.

C. Calculations and Programming

Production effluent were collected incrementally in the graduated cylinders. For each increment, water and solvent-oil were reported. The compositional analysis of solvent-oil production was done by chromatography and/or with the refractometer. The availability of an integrator hooked into the chromatograph expedited the operations and reduced the calculation time.

Having the injection production data in increments, and the compositional analysis, a program was developed to calculate the percent residual oil recovery and oil, solvent and water production in pore volumes as a function of pore volume injected (Appendix A). This program can be used as long as all the fluids are liquid and if liquid input equals liquid output.

FIG. 1

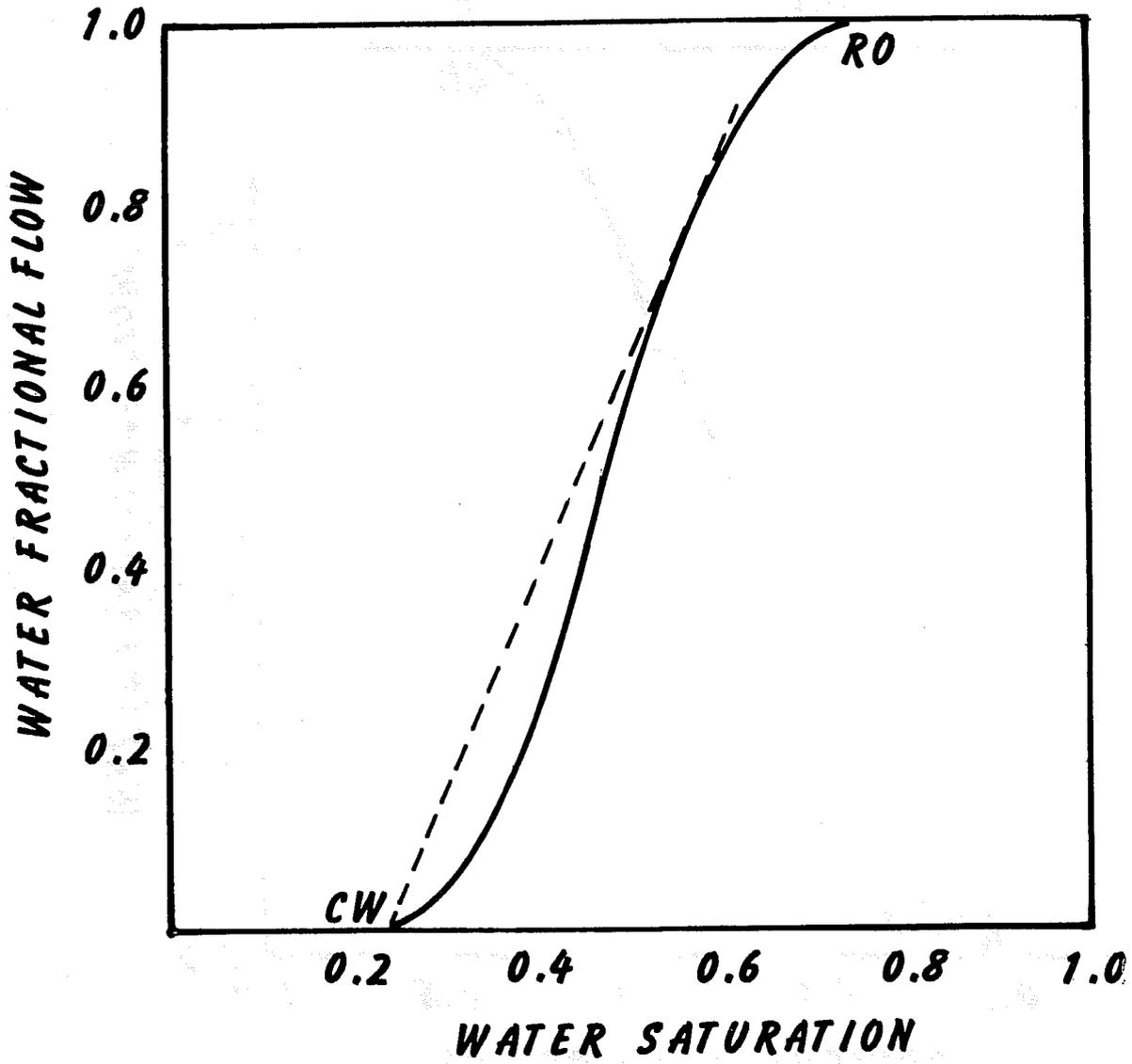


FIG. 2

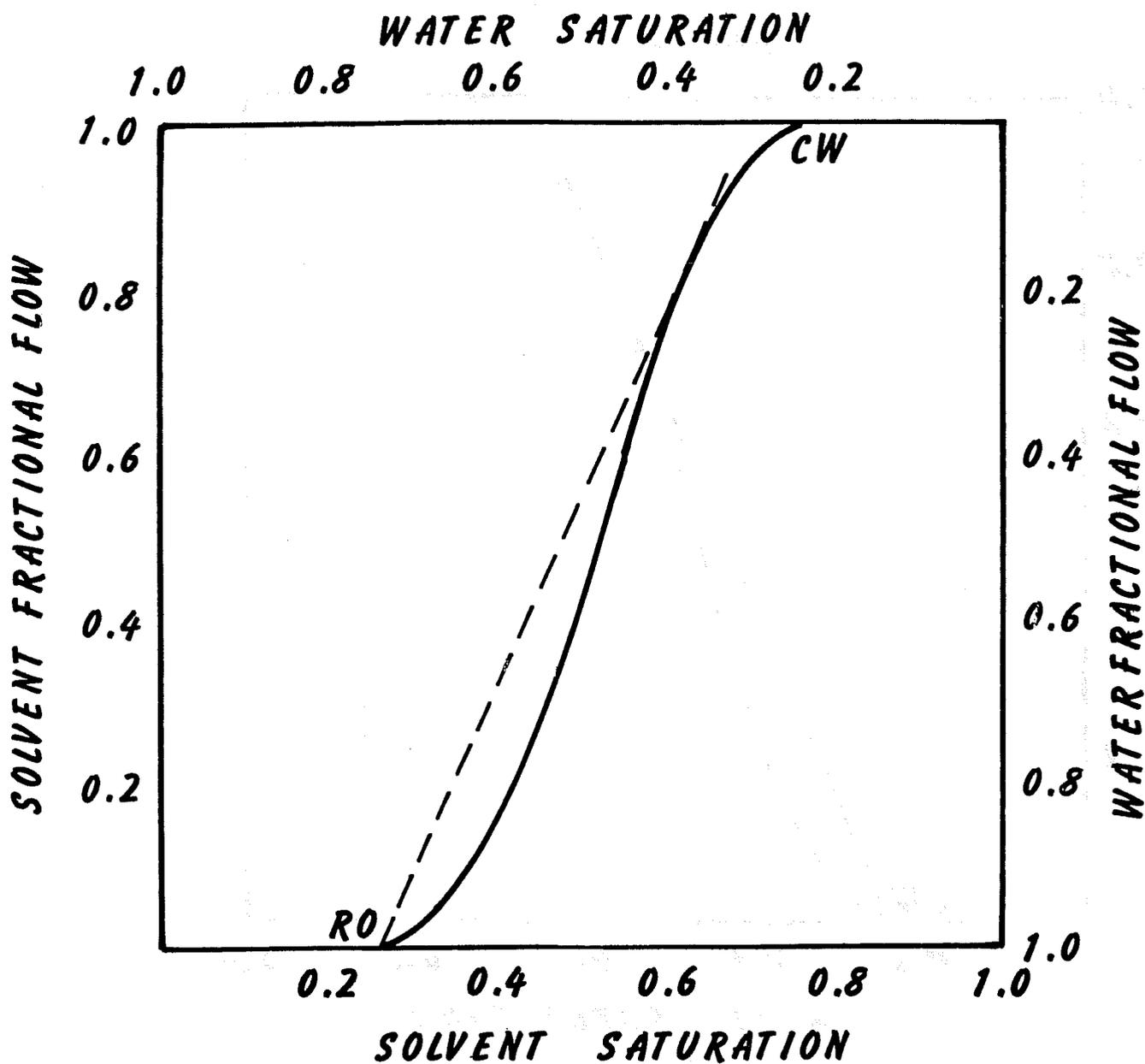


FIG. 3

SLIGHTLY UNFAVORABLE SOLVENT/WATER
VISCOSITY RATIO (3)

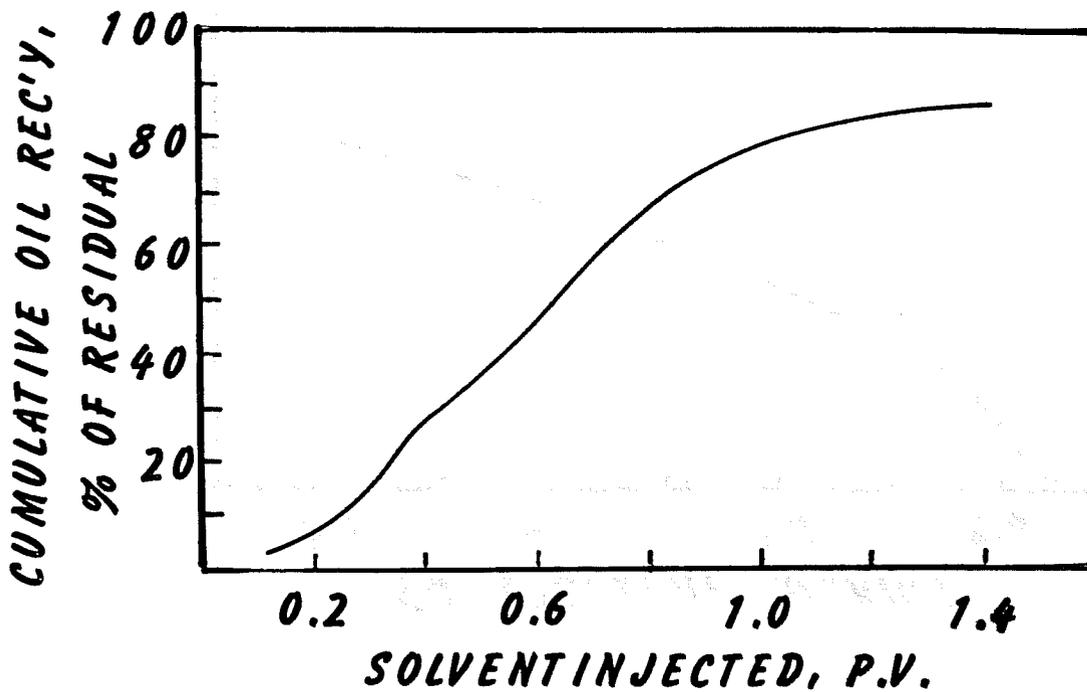
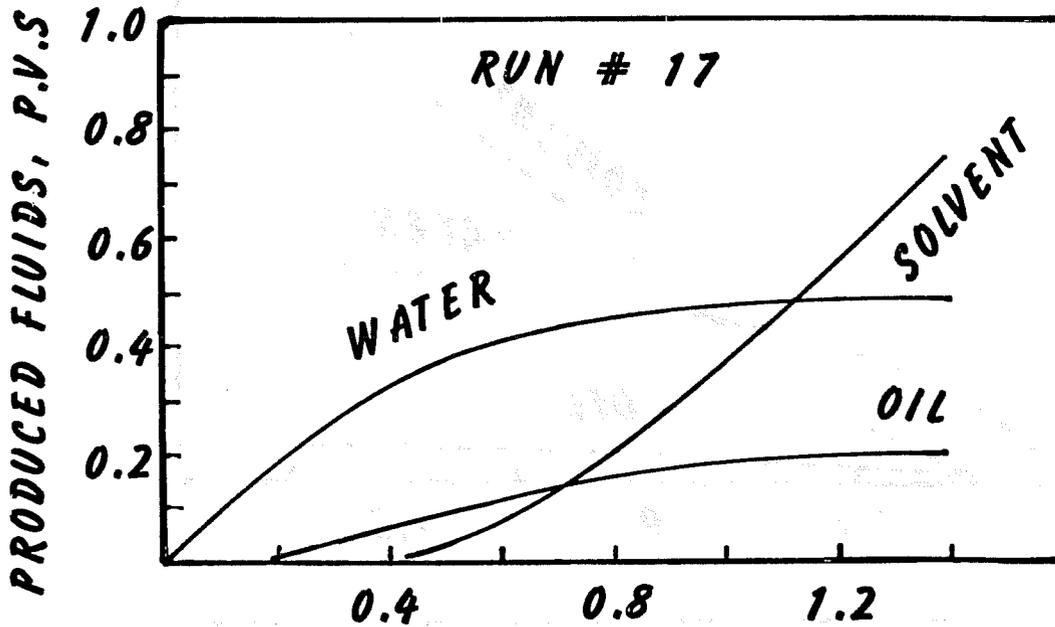


FIG. 4
UNFAVORABLE SOLVENT/WATER
VISCOSITY RATIO (16)

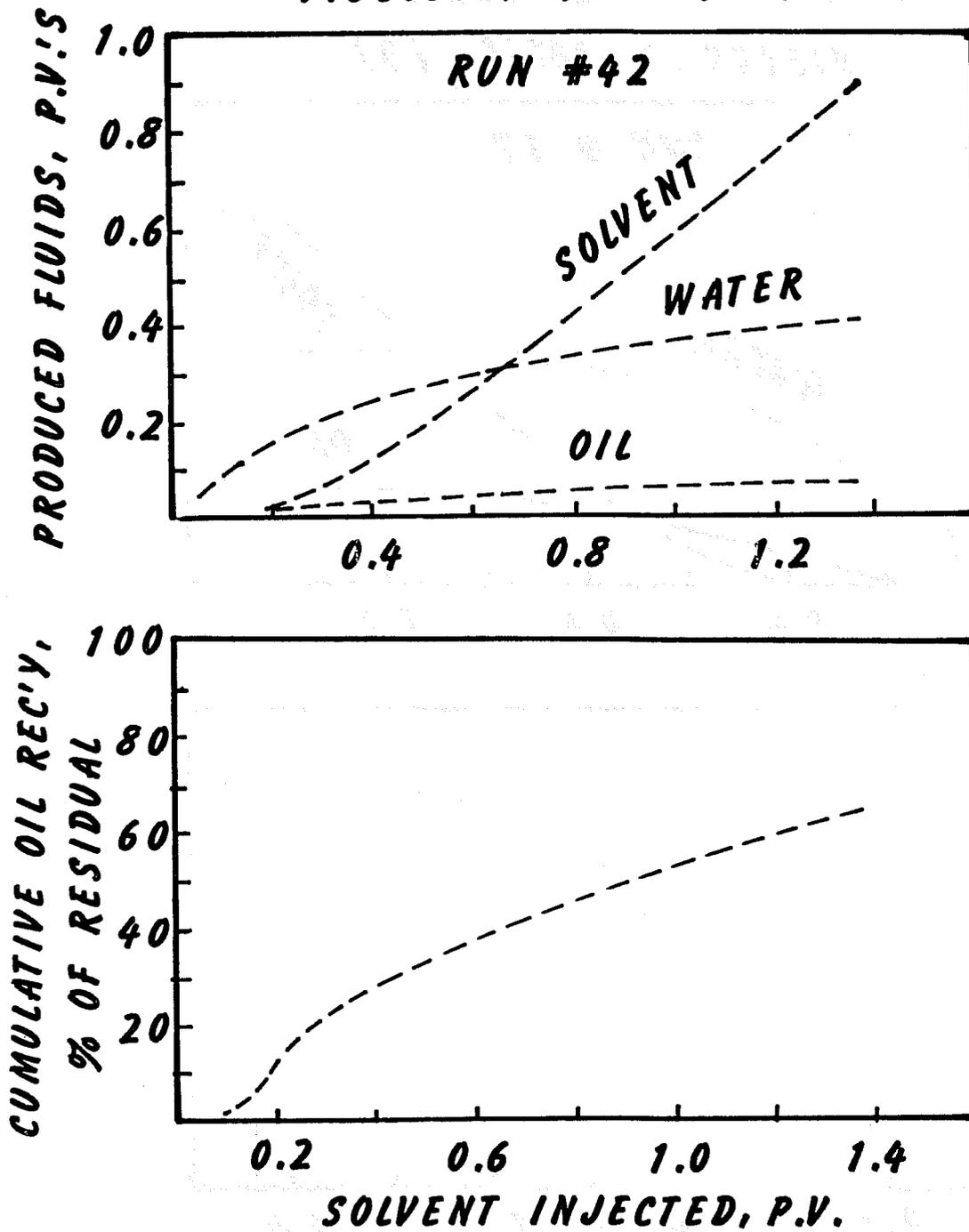


FIG. 5

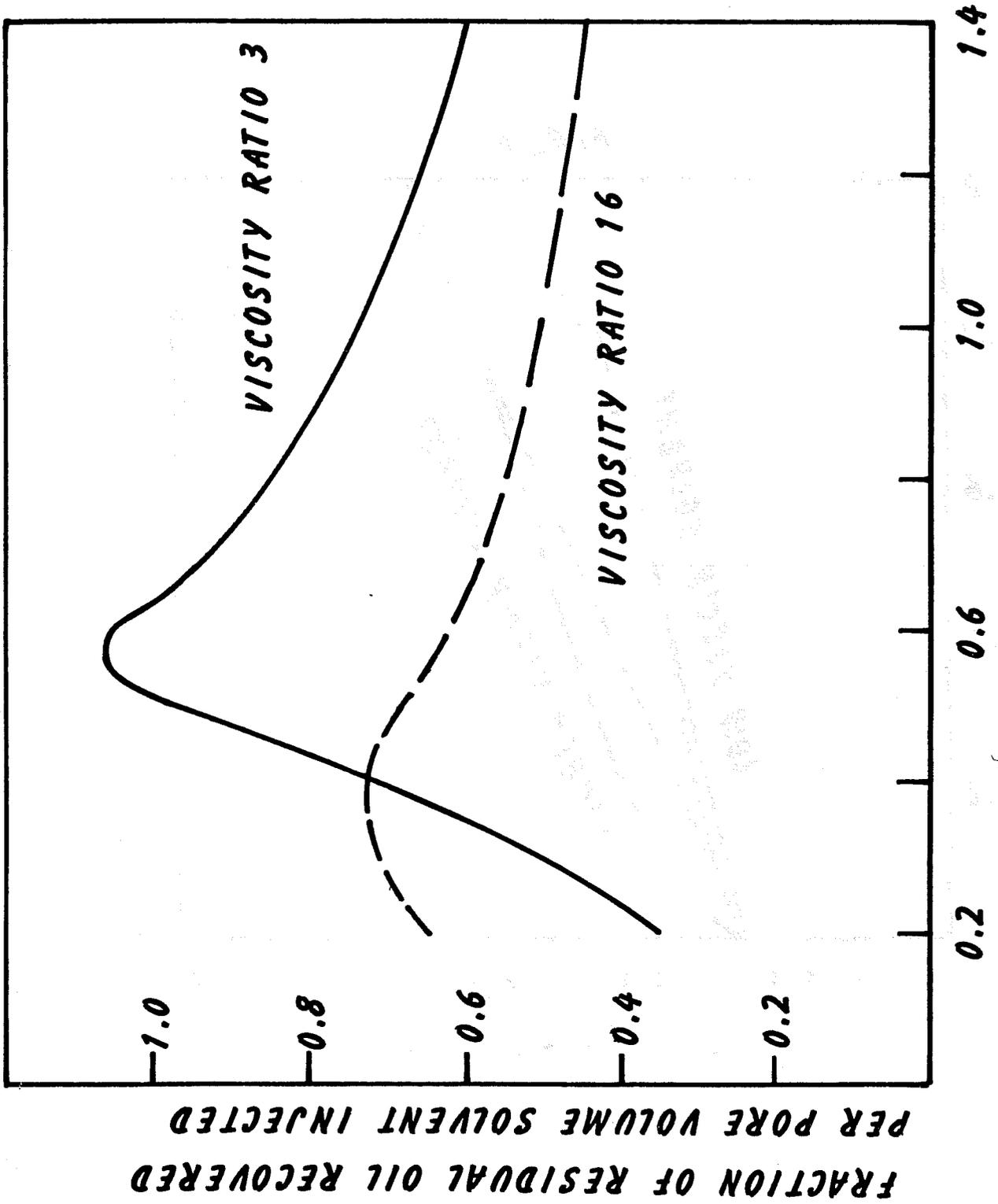


FIG. 6

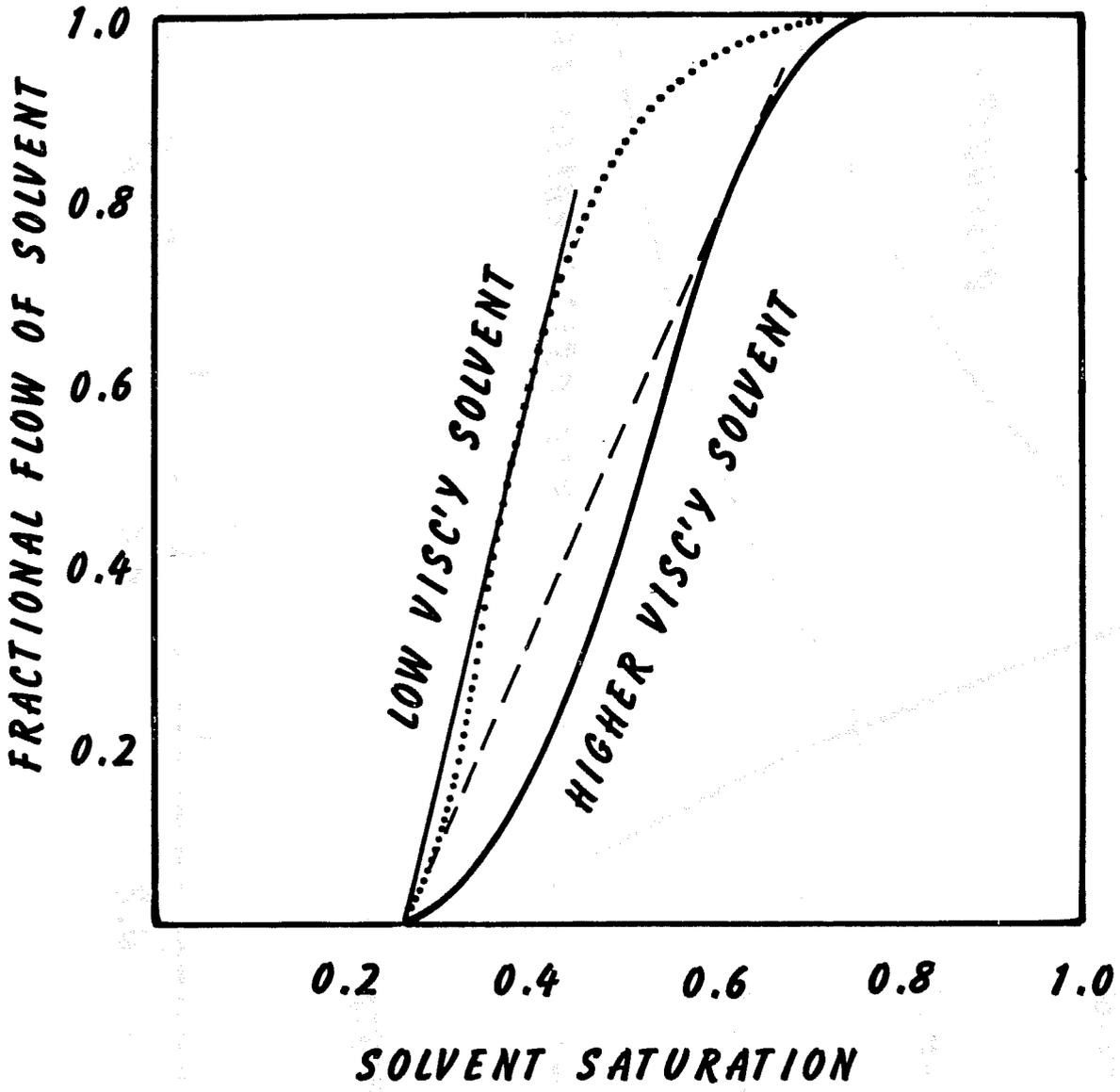
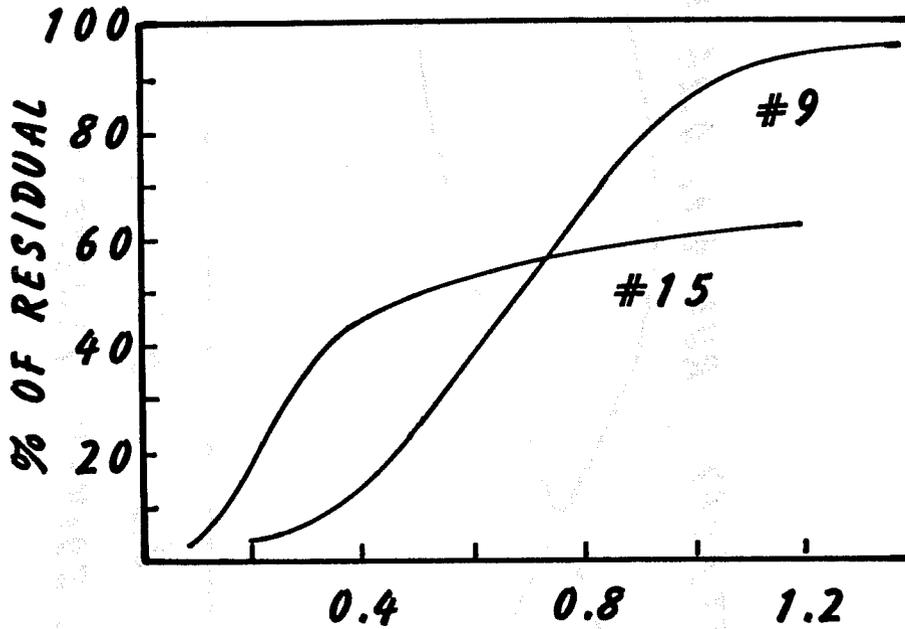


FIG.7
COMPARISON OF NORMAL RATE
AND A LOW RATE

CUMULATIVE OIL RECOVERY,



PRODUCED WATER, P.V.

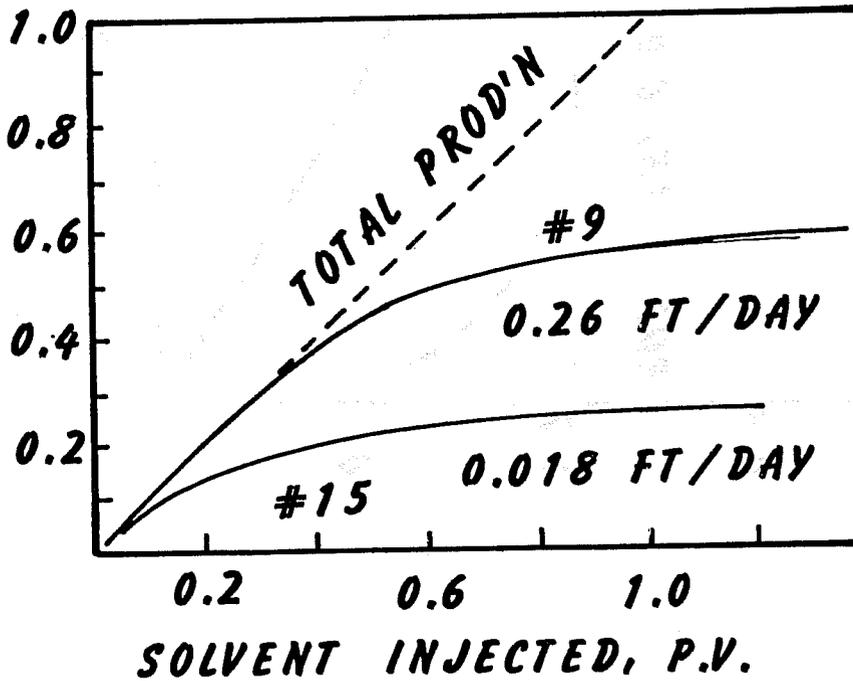
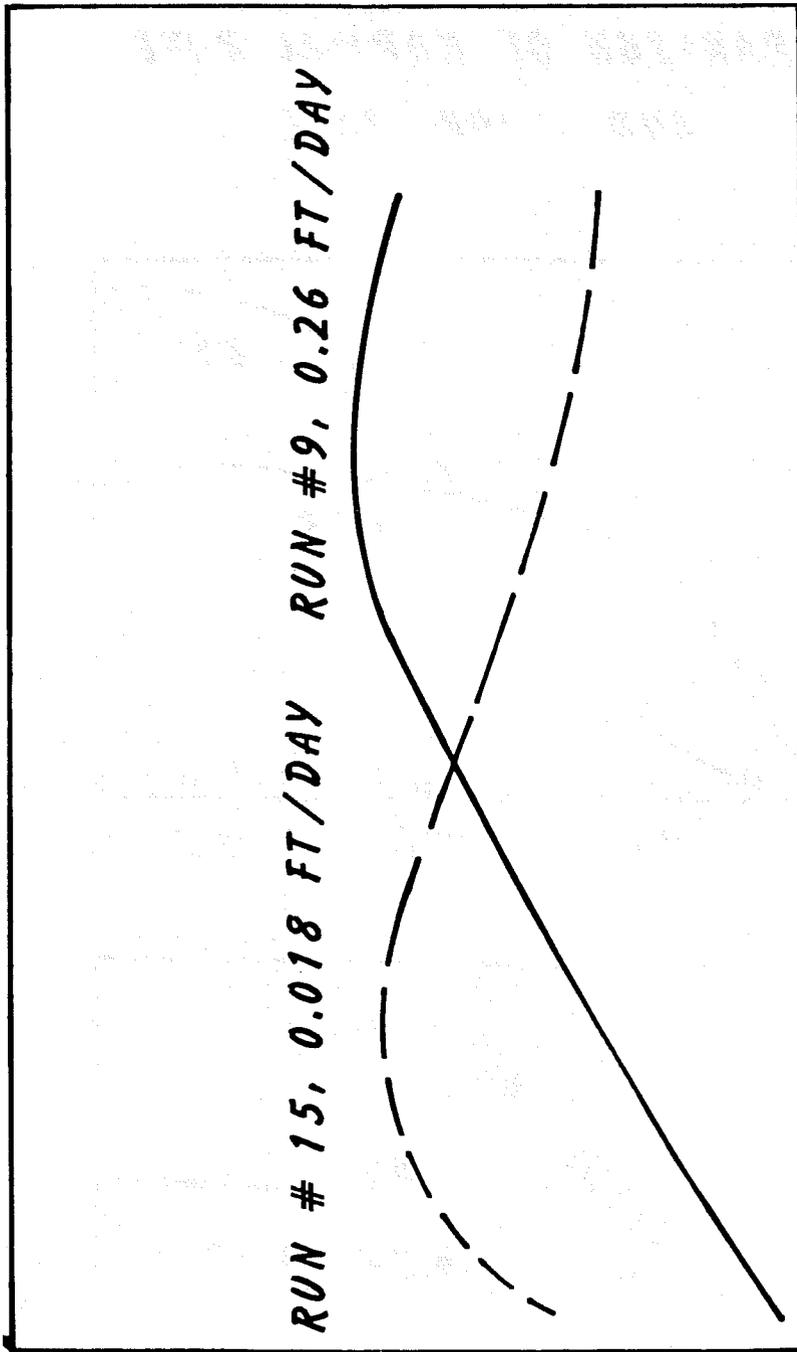


FIG. 8

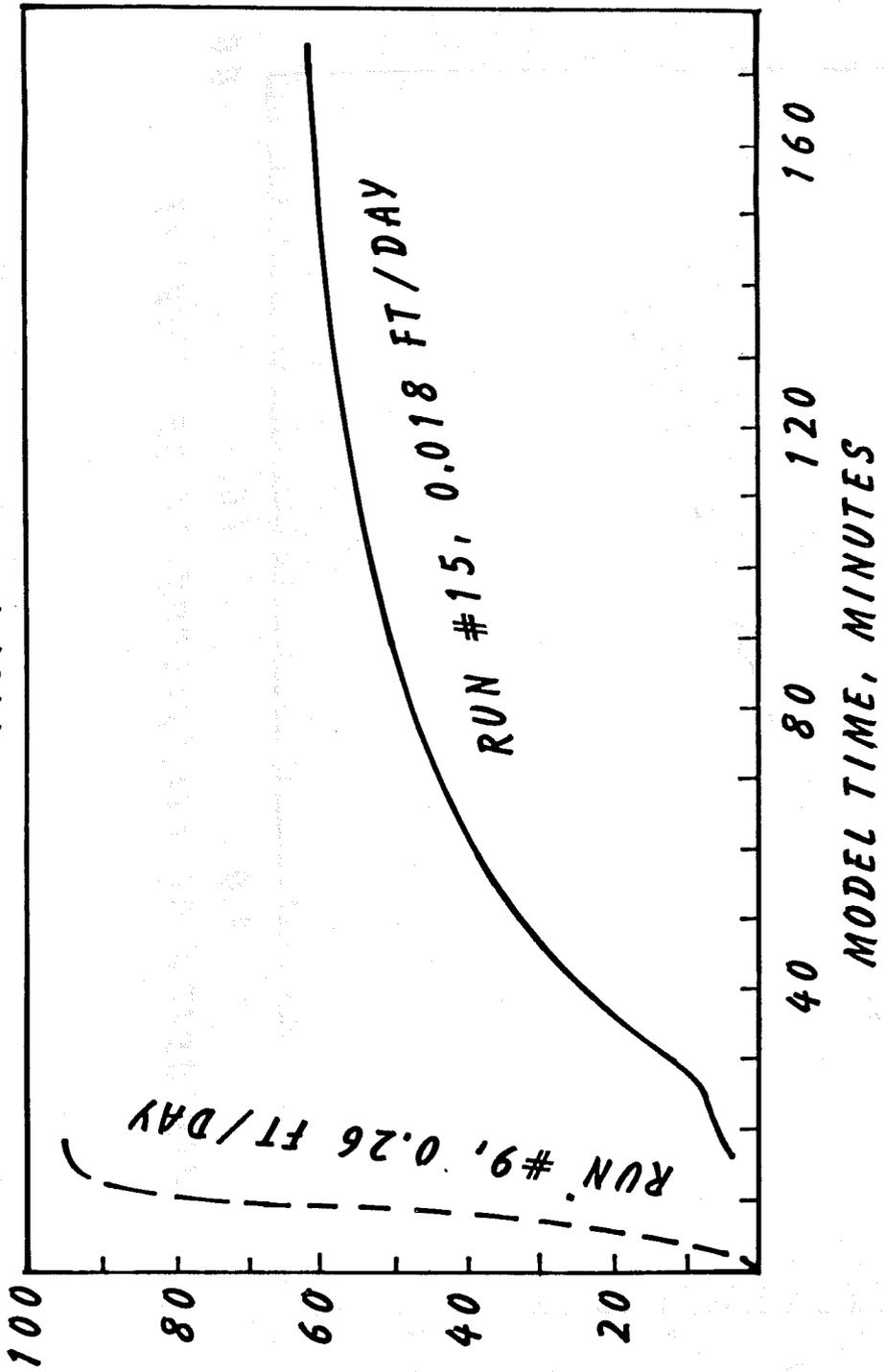
P.V.'S OIL RECOVERED PER P.V. SOLVENT INJECTED



0.2 0.4 0.6 0.8 1.0 1.2
P.V. SOLVENT INJECTED

CUMULATIVE OIL RECY, % OF RESIDUAL

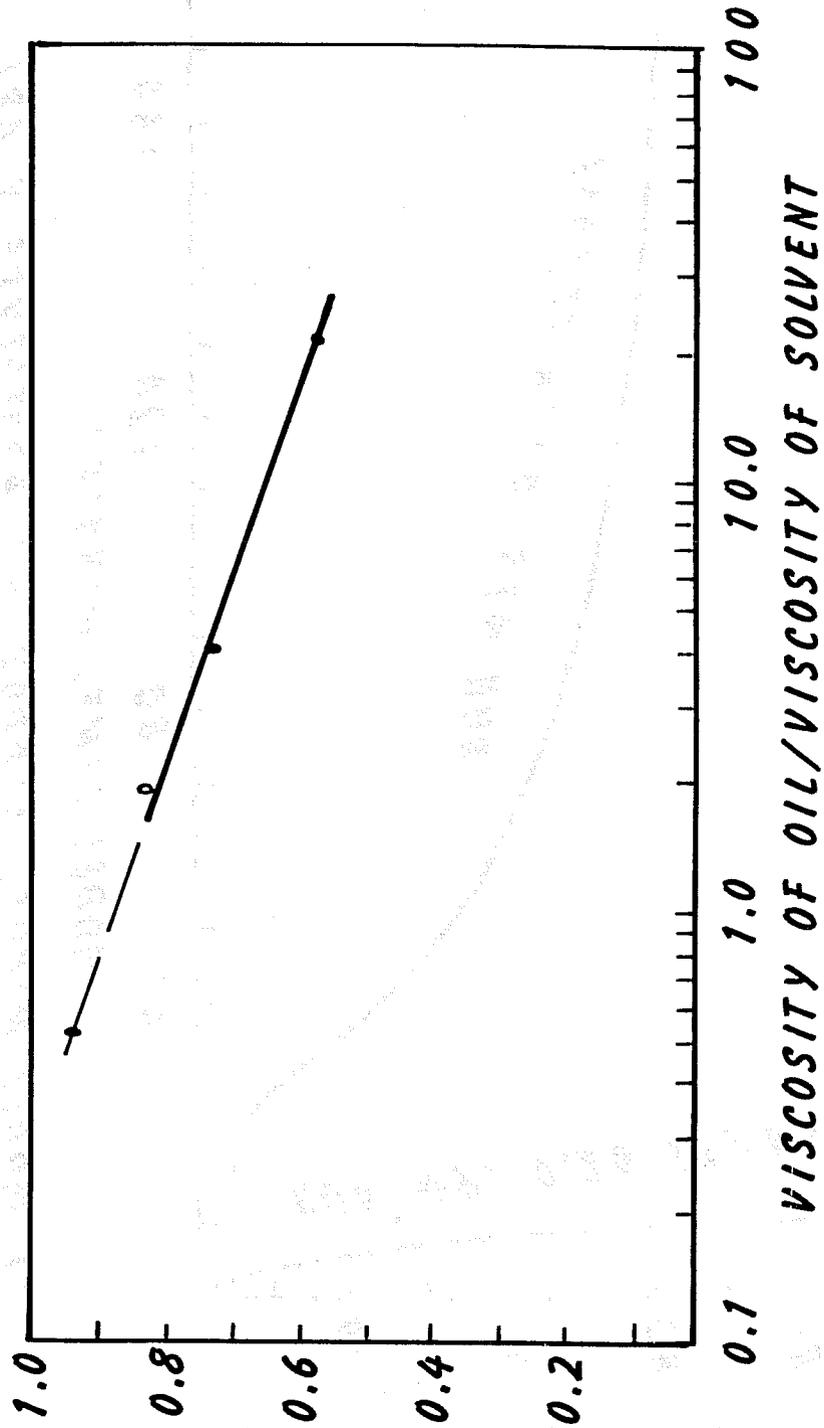
FIG. 9



11 MODEL MINUTE APPROX. 0.5 PROTOTYPE YEAR/
ILLUSTRATING THE DIFFERENCE IN TIME AVAILABLE FOR
MOLECULAR DIFFUSION AS A FUNCTION OF FLUID VELOCITY

FIG. 10

RECOVERY PARAMETER, FRACTION OF OIL RECOVERED
AFTER SOLVENT BREAKTHROUGH (TO 1.4 P.V.'S INJECTED)



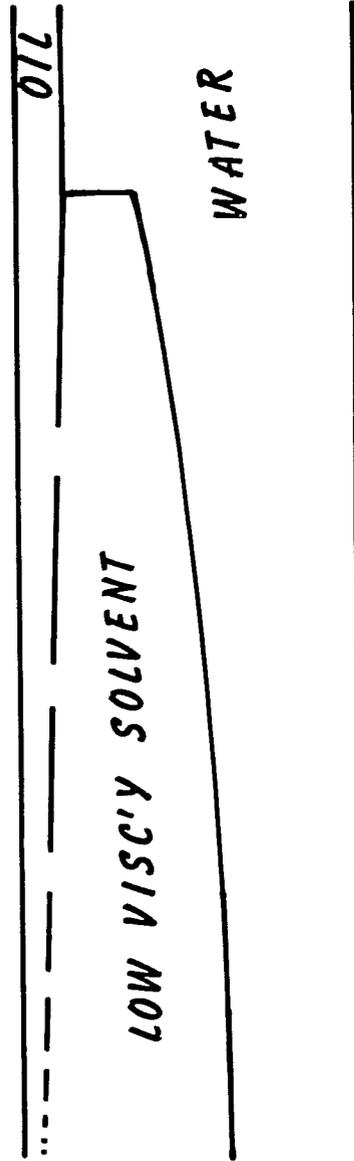
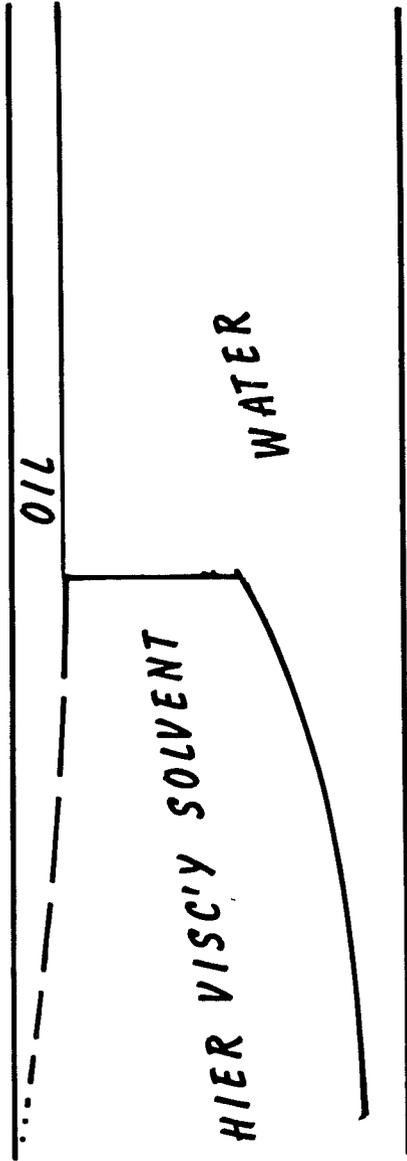


FIGURE 11: ILLUSTRATING THE DIFFERENCE IN SATURATION DISTRIBUTION RESULTING FROM DIFFERENCES IN SOLVENT VISCOSITY

