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PREDICTION OF TRACER BEHAVIOR IN FIVE-SPOT FLOW

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ABSTRACT

Equations are developed to predict the time of tracer breakthrough, the peak concentration of the tracer, and the general form of the breakthrough curve in a 5-spot flood. It is shown that these results depend on the amount of stratification of the reservoir, the volumes injected and produced, the natural dispersion coefficient of the tracer in the reservoir, the amount of tracer injected, plus all the reservoir volume parameters (i.e. well spacing, porosity, thickness).

Many laboratory data are available on the breakthrough characteristics of a 5-spot flood, also much data is available on the natural linear dispersion coefficients of reservoir rock. To derive the equations, these data were combined and several assumptions were made. It was also necessary to graphically differentiate the breakthrough data. Thus it should be recognized that the final equations likely have some error. However, this should not invalidate their use, for the method and logic behind the derivation are sound, and thus the form of the final equations should be close to correct. In this paper, the prediction equations are used in a reverse sense. That is, the detailed tracer production history from a field test is used to estimate permeability variation in a 5-spot.

INTRODUCTION

Tracers have been used for many years in reservoir floods to help the operating engineer understand the flow characteristics. Generally this use has been entirely qualitative. The results of time-of-flight, peak concentrations at the producing wells, concentration history, and directional flow have been used only to substantiate that channelling does nor does not exist. No attempts have been made to predict quantitatively the tracer breakthrough behavior that might be expected from different reservoir characteristics.

In the past couple of years it has become apparent that some prediction technique could be well used to supplement the other tools available to the reservoir engineer. It is becoming increasingly important that maximum recovery be obtained from a flood, and any quantitative information about the reservoir can be of help in achieving this maximum. The work reported here is a step in this direction -- an attempt to quantify the tracer behavior.

Equations are developed to predict the time of tracer breakthrough, the peak concentration of the tracer, and the general form of the breakthrough curve in a 5-spot flood. Tracer production history from a field test are compared to the behavior as predicted by the equations. As more field data become available, and more sophisticated derivations are made, the equation constants can be adjusted and better predictions and interpretations will be possible in the future.

These calculations were directed for use of tracers where the mobility ratio is near unity. In general, this is valid in many waterfloods and almost all gas cycling projects. The method of approach, however, can be used whenever the reservoir coverage and dispersion characteristics can be approximated. In systems where the mobility ratio is inherently unfavorable and fingering is predominant, the approach cannot yet be used because of the limited knowledge of dispersion in these systems. Thus, at present, this approach would be only partially successful in miscible flooding calculations.

DEVELOPMENT OF EQUATIONS

This section of the paper covers the method of calculating tracer behavior in a homogeneous 5-spot system when the mobility ratio is 1:1. Two characteristics affect the breakthrough history of the tracer; the mixing due to dispersion, and the pattern sweep efficiency. These effects are treated separately and then mathematically combined.

Dispersion or Mixing

When one material miscibly displaces another in a porous medium, mixing occurs in a manner similar to Fick diffusion, except the constant of mixing is changed. In radial flow this equation can be expressed as follows:

$$\frac{\partial C}{\partial r} + \frac{2\pi\phi r}{Q}\frac{\partial C}{\partial t} = \frac{2\pi\phi r K}{Q}\frac{\partial^2 C}{\partial r^2} \qquad (1)$$

where C = Concentration (any consistent units)
K = Dispersion coefficient - analogous to the Fick diffusion coefficient (ft^2/sec)
r = Radius (ft)
t = Time (sec)
Q = Volumetric injection rate (ft^3/sec-ft)

For convenience in writing, the term, $Q/2\pi\phi$, can be called Q'. Another simplification can be made if the dispersion coefficient is assumed proportional to velocity. Experimental evidence shows this is a close approximation[1]. Then the term, $2\pi\phi rK/Q$ (or rK/Q'), can be replaced by α (a constant for any given porous medium). The resulting equation is

$$\frac{\partial C}{\partial r} + \frac{r}{Q'}\frac{\partial C}{\partial t} = \alpha\frac{\partial^2 C}{\partial r^2} \qquad (2)$$

Raimondi et al[2] have shown that this equation can be solved if one realizes that the term on the right hand side of the equation is quite small compared to the other terms. The value of the second partial can then be approximately calculated by assuming the right hand side is zero.

$$\frac{\partial C}{\partial r} + \frac{r}{Q'}\frac{\partial C}{\partial t} \simeq 0 \qquad (3)$$

The expression for the second partial then becomes,

$$\frac{\partial^2 C}{\partial r^2} \simeq \frac{-1}{Q'}\frac{\partial C}{\partial t} + \frac{r^2}{(Q')^2}\frac{\partial^2 C}{\partial t^2} \qquad (4)$$

and Equation 2 can be replaced by,

$$\frac{\partial C}{\partial r} + \frac{r}{Q'}\frac{\partial C}{\partial t} \simeq -\frac{\alpha}{Q'}\frac{\partial C}{\partial t} + \alpha\left(\frac{r}{Q'}\right)^2\frac{\partial^2 C}{\partial t^2} \qquad (5)$$

In Equation 5 there are two multipliers on $\partial C/\partial t$: r/Q' and α/Q'. Experimental data on α (Ref. 1) shows that it is always considerably smaller than one foot; so it can properly be neglected compared to r, and Equation 5 can be simplified to:

$$\frac{\partial C}{\partial r} + \frac{r}{Q'}\frac{\partial C}{\partial t} = \alpha\left(\frac{r}{Q'}\right)^2\frac{\partial^2 C}{\partial t^2} \qquad (6)$$

The equation can be further simplified by changing variables.

Define:

$$\tau = t - \frac{r^2}{2Q}$$

and

$$\rho = \frac{r^3}{3}$$

The resulting expression is:

$$\frac{\partial C}{\partial \rho} = \frac{\alpha}{Q'^2}\frac{\partial^2 C}{\partial \tau^2} \qquad (7)$$

When one fluid is displacing another in an infinite, radial porous medium, the solution to Equation 7 is:

$$\frac{C}{C_o} = \frac{1}{2}\,\mathrm{erfc}\left(\frac{\tau}{2\sqrt{\alpha\rho/Q'^2}}\right)$$

$$= \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q't - r^2/2}{2\sqrt{\alpha r^3/3}}\right) \qquad (8)$$

When a tracer is injected, it is necessary to include both the front and back edges of the tracer slug. The solution will then contain two terms of the form similar to Equation 8. For symmetry it is convenient to have the reference point at the middle of the tracer slug. If the tracer is injected for a time, t_1, the reference points will be at $t \pm t_1/2$, and the result is;

$$\frac{C}{C_o} = \frac{1}{2}\,\text{erfc}\left(\frac{Q'(t+t_1/2) - r^2/2}{2\sqrt{\alpha r^3}/3}\right) - \frac{1}{2}\,\text{erfc}\left(\frac{Q'(t-t_1/2) - r^2/2}{2\sqrt{\alpha r^3}/3}\right) \qquad (9)$$

We wish to know the peak concentration, or midpoint concentration, C_{mp}, of the tracer slug. At this point $Q't = r^2/2$, and the result is,

$$\frac{C_{mp}}{C_o} = \text{erf}\left(\frac{Q't_1}{4\sqrt{\alpha r^3}/3}\right) \qquad (10)$$

The term $Q't$, is a measure of the amount of tracer injected. For easier visualization of the variables it might be simpler to look at this term in relation to a width of tracer slug. If the slug moved out into the reservoir without mixing, its undiluted "width", W, would be expressed as $rW = Q't_1$, and Equation 10 could be written,

$$\frac{C_{mp}}{C_o} = \text{erf}\left(\frac{\sqrt{3}\,W}{4\sqrt{\alpha r}}\right) \qquad (11)$$

By comparison, for dispersion of a tracer in a linear flow for a distance, L, the result is,

$$\frac{C_{mp}}{C_o} = \text{erf}\left(\frac{W}{4\sqrt{\alpha L}}\right) \qquad (12)$$

so the radial and linear equations differ only in the factor $\sqrt{3}$.

When the argument of the error function is less than about 0.1, the function becomes linear, with the constant 1.13. In tracer work, the desired output concentration is almost always less than one tenth of the input concentration, so Equation 11 can be simplified to,

$$\frac{C_{mp}}{C_o} = \frac{1.13\sqrt{3}\,W}{4\sqrt{\alpha r}} \qquad (13)$$

Flow in a 5-spot is not radial, but it is possible to approximate the geometry of a 5-spot system with a radial model. If a circle is drawn with its center at the injection well and the circumference cutting the four surrounding producing wells, and then the circle is folded back on itself as shown in Figure 1, the shape of the front is very similar to the actual front in a 5-spot displacement at breakthrough. Of great importance is that the length of the front thus formed is very close to the length of the actual front in 5-spot flow. And a study of Equation 13 shows that the front length is the most important parameter affecting the mid-point concentration.

The mass of tracer injected is equal to the perimeter times: width, height, porosity saturation, concentration and density. For a waterflood tracer this is

$$m = 2\pi L W h \phi S_w C_o (62.4) \qquad (14)$$

Where L = Distance from injector to producer (ft)

C_o = Injected concentration (weight fraction)

Equations 13 and 14 can now be combined to determine the amount of tracer to inject for a desired peak concentration, remembering that r, in Equation 13 is now the interwell distance, L.

$$m = 800\, h \phi S_w C_{mp} L^{1.5} \alpha^{.5} \qquad (15)$$

Areal Sweep Effects

Equation 15 gives us the concentration of the tracer flowing in the reservoir. However, this is not the same as the concentration flowing out of the wellbore, for the geometry of the 5-spot system causes the tracer front to be diluted at the wellbore. This can be explained as follows.

Assume we have a homogeneous 5-spot filled with fluid "A" and inject fluid "B" which has the same mobility. Also assume no mixing takes place at the front (later the areal sweep effects will be combined with the mixing effects). Thus "B" is injected as a sharp front and will remain as a sharp front. The resulting breakthrough curve looks like curve, 1, in Figure 2a. Note that the percent "B" rises after breakthrough, but it requires a large injection volume before the producing concentration climbs to 100 percent "B". The "B" that is flowing in the reservoir, however, is at 100 percent concentration.

Now consider a case where a slug of "B" is injected and this in turn is followed by "A". Again assume no dispersion occurs and slug "B" remains sharp and undiluted. The breakthrough curve for the front of the "B" slug will remain the same, and the breakthrough curve for "A" following "B" will be identical in shape--merely lagging the first curve as shown in curve 2, Figure 2a. At any point in the production history, the concentration of "B" being produced is equal to the vertical distance in the "B" area of Figure 2a, and the resulting "B" concentration production curve looks like Figure 2b. Notice that the peak producing concentration of "B" is considerably less than 100 percent, even though the concentration of "B" flowing in the reservoir is 100 percent.

When the tracer becomes dispersed (or mixed) in the reservoir it is convenient to think of the tracer being composed of many small slugs, each with a different concentration. The highest concentration is in the center and progressively lower values are ahead and behind. This concept is shown in Figure 2c. In this case the "B" output concentration curve can be calculated by vertically summing the concentration contributions of each small segment, and the resulting curve looks something like Figure 2d. The general shape of this curve is similar to the undiluted slug of Figure 2b, but it is less sharply peaked; and, of course, has a lower concentration due to the mixing.

The problem now is to develop these qualitative concepts into numbers and equations. For the 5-spot areal sweep information the data of Dyes, Caudle, and Erickson[3]; Caudle and Witte[4]; and Fay and Prats[5] were used. Since these data differed slightly from each other, they were averaged and the resultant curve plotted in Figure 3. This curve could not be conveniently fit to an equation, so it was differentiated graphically, plotted as the solid stair-step line of Figure 4, and emperically fit to the following equation.

$$\log\left[\log\left(\frac{1.07}{1.07 - F_D}\right)\right] = -.0410 + .581\log(Q_i - .72)$$

$$\text{for } .72 < Q_i < 2.29 \qquad (16)$$

Where F_D = Fraction of displacing fluid in the producing stream
Q_i = Volume injected and produced (effective pore volumes)

This is plotted as the dashed line of Figure 4.

Combining the Breakthrough and Dispersion Data

Equations 11 or 13 predict the concentration at the midpoint, but the concentration ahead of and behind the midpoint is also needed. This is an e^{-x^2} type term, which can be extracted from Equations 11 or 13 as follows,

$$\frac{C_1}{C_{mp}} = e^{-\frac{3(\Delta r)^2}{4\alpha L}} \qquad (17)$$

Where C_1 = Concentration at some point r_1 near the midpoint, L
$\Delta r = L^1 - r_1$

Since Equation 16 is in pore volume units, and we wish to combine it with Equation 17, it will be necessary to change Equation 17 to pore volume units. The volume of a tracer segment is $2\pi\phi\Delta rLh$ and one pore volume is $2\phi L^2h$, so an increment in pore volume is,

$$\Delta(PV) = \frac{2\phi\pi\Delta rLh}{2\phi L^2h} = \frac{\pi\Delta r}{L} \qquad (18)$$

and the concentration profile becomes,

$$\frac{C_1}{C_{mp}} = e^{-\frac{3L(\Delta PV)^2}{4\pi^2\alpha}} \qquad (19)$$

Assume now that a tracer slug has been injected, it is followed by a volume of water (V_i) and the midpoint of the tracer is along the front at V_i. Equation 19 states that the tracer is distributed everywhere in the reservoir at a concentration proportional to $e^{-(\Delta PV)^2}$. According to Equation 16, any tracer at a location 2.29 or more pore volumes out from the injection well will have already been produced, and any tracer at a location less than .72 pore volume has not yet started to be produced. The rest of the tracer is being produced at a rate depending on its location. To determine the total tracer production it is necessary to sum all contributions from .72 to 2.29 pore volumes, thusly.

$$\frac{C(V_i)}{C_{mp}} = \int_{.72}^{2.29} \frac{dF_D}{dQ_i} e^{-\frac{3L(Q_i-V_i)^2}{4\pi^2\alpha}} dQ_i \qquad (20)$$

Where $C(V_i)$ = Producing concentration as a function of volume injected.
F_D = Fraction displacing fluid.
V_i = Volume injected (pore volumes).
Q_i = Location volume (pore volumes).

This is the same "summing" used earlier to get from Figure 2c to Figure 2d.

Unfortunately, Equation 20 cannot be integrated analytically due to the complex relationship between F_D and Q; so it was integrated numerically, giving C versus V_i for various values of L/α. The results of these calculations are plotted in Figure 5. Note that, for all spacings and dispersion coefficients, the peak concentration producing from the well is considerably less than the peak concentration in the reservoir.

The peak concentrations of Figure 5 were plotted on log-log paper in Figure 6. Emperically they were found to fit a straight line with the following equation.

$$\frac{C_p}{C_{mp}} = 2.63 \left(\frac{L}{\alpha}\right)^{-.235} \qquad (21)$$

Where C_p = Peak concentration produced from the reservoir.

Equation 21 can now be combined with Equation 15 to give us a working equation for 5-spot geometry.

$$m = 304h\phi S_w C_p \alpha^{.265} L^{1.735} \qquad (22)$$

For convenience, it is easier to use the concentration, C_p, in parts per million. This is the usual method of expressing tracer concentration. The inter-well distance is more easily handled in hundreds of feet. With these changes, the equation becomes,

$$m = .90h\phi S_w C_p \alpha^{.265} L^{1.735} \qquad (23)$$

Where C_p = Peak concentration producing from the well (ppm)
L = Distance from injector to producer (hundreds of feet)

Effect of Outside Wells

Only the flow in the pattern has been included so far in the calculations. In a developed 5-spot pattern, each producing well receives fluids from four wells. Thus, if the pattern is balanced, the tracer is further diluted by a factor of four.

If the pattern is not balanced, the flow system is not so simple, for the basic sweep pattern will be changed from that used to arrive at Equation 23. The effect of the sweep pattern change cannot be properly calculated because data are not available. However, the equations can be partially corrected by accounting for the total volumes injected and produced. This is shown in the following example.

For instance, assume that an injection well is taking 1000 B/D, and it is surrounded by four producers making 600 B/D each. If the reservoir is liquid filled and there is dynamic balance of flow, each producer will get 250 B/D from the injector and 350 B/D from outside the pattern. Thus the actual peak concentration is smaller than calculated from Equation 23 by the ratio 250/600.

If the pattern is balanced, each producer will make 1000 B/D. Each producer will be getting 250 B/D from the injector and 750 B/D from outside the pattern. The peak concentration will be smaller by the ratio 250/1000.

These examples illustrate the idea, but they are considerably simpler than the usual field case.

Stratification of Reservoir

All the previous calculations were based on a homogeneous reservoir. Unfortunately, such does not exist. But it is possible to make some allowance for the heterogeneity of the actual reservoir with some further assumptions.

One of the most common methods of handling inhomogeneity is to mathematically divide the reservoir into layers, assign a permeability to each layer, and assume no cross flow. We should not believe these assumptions too wholeheartedly, but this model has a history of passable reservoir predictions to back up its usage.

If a reservoir is divided into layers, the amount of tracer going into each layer is proportional to its permeability. So, from Equation 15, the concentration flowing in that layer will also be proportional to its permeability. At the producing wellbore the tracer from a given layer will be diluted by flow coming in from other layers. The dilution is proportional to the kh product of the layer compared to the total kh of the reservoir. So the resulting producing concentration is as follows

$$C_i = C_p \frac{k_i}{k_{avg}} \left(\frac{h_i k_i}{\Sigma h_i k_i} \right) = C_p \frac{h_i}{h} \left(\frac{k_i}{k_{avg}} \right)^2 \qquad (24)$$

C_i = Concentration peak from the ith layer
C_p = Peak concentration if the reservoir is homogeneous (from Equation 23)
k_i = Permeability of the ith layer
k_{avg} = Average permeability of the reservoir
h_i = Height of the ith layer
h = Height of the reservoir

Since the flow rate through the ith layer is proportional to its permeability, the time to breakthrough of that layer is inversely proportional to its permeability, as follows.

$$t_i = t_{avg} \frac{k_{avg}}{k_i} \qquad (25)$$

Where t_i = Time to breakthrough of the ith layer
t_{avg} = Time to breakthrough of the homogeneous reservoir

When Equations 23, 24 and 25 and Figure 5 are used in conjunction with the effect of the outside wells, the peak concentration, the concentration profile, and breakthrough time of each layer can be calculated for any given 5-spot condition. In actual practice the contribution from the most permeable layer, or layers, will be most important.

FIVE-SPOT FIELD TEST

A 2 1/2 acre inverted 5-spot having approximately 12 feet of net pay was chosen for a test. The average porosity was 26 percent and water saturation was 55 percent. From core data, the average air permeability of the sand was 1500 md with indications of a 5000 md streak approximately one foot thick. Laboratory mixing data on the core gave an α of 0.05 ft. The orientation of the pattern wells is shown in Figure 7. Further data on the test is given in Reference 6.

Two hundred pounds of ammonium thiocyanate and 150 pounds of potassium iodide were injected simultaneously as tracers. During the test, the injection well averaged 600 BWPD and the producing rates were as follows: Well A, 260 BWPD; Well B, 160 BWPD; Well C, 140 BWPD; and Well D, 240 BWPD; for a total of 800 BWPD. The data on breakthrough of the tracers is shown in Figures 8, 9 and 10 for Wells A, C and D. No tracer was ever detected from Well B.

Since no tracer was found in Well B, it was assumed that only fifty barrels per day of the injected water were moving toward this well. The remaining water was distributed among the other three wells according to their production rate; Well A 225 BWPD, Well C 120 BWPD, and Well D 205 BWPD. The total tracer produced from these wells indicates that this assumption is sound, for about equal volumes were produced from Wells A and D with considerably less from Well C.

The ammonium thiocyanate curve of Well D was chosen for detailed analysis. Since the injection well was down for about four days, it was felt that it would be meaningless to attempt to match the concentration curve during and after that period. So the tracer elution curve was approximated from the period of 2000 bbls to 4000 bbls production using Equations 23, 24 and 25 and Figure 5. The resulting match is shown in Figure 11.

Three permeable streaks were used to arrive at Figure 11: 4110 md, 0.99 ft thick; 3420 md, 1.00 ft thick; and 2980 md, .59 ft thick. Notice that the shape of the curve is quite close to the thiocyanate curve of Figure 10. Although the detailed spikes and peaks are missing, the curve basically consists of two major peaks as shown. On the other hand the potassium iodide curve of Figure 10 is basically a single broad hump covering the sampe production interval as the thiocyanate. So the "double peak" approximation of Figure 11 is not valid for the iodide. Since the percentage of iodide and thiocyanate recovered was virtually the same in all three wells, we must conclude the iodide curve is as valid as the thiocyanate curve. Rather than emphasizing the exact values calculated for the permeability streaks of Figure 11, the curves should be considered in a broader sense to conclude there is a zone about 2 1/2 feet thick which ranges from about 2 to 3 times the average permeability.

Since the curves for Well A are similar to Well D, the conclusions should be the same for this quadrant.

The injection well was down during the period when Well C was peaking out. Since this undoubtedly disrupted the flow pattern (notice the drop in tracer concentration in all three wells during this period), no analysis was attempted on Well C.

It is obvious that a Northwest-Southeast permeability trend exists in this pattern. This could possibly have been expected from the differing production rates of the four wells; but it was dramatically pointed out by these tracer results. This is especially interesting in view of the fact that the core analysis data indicated no such permeability trend.

CONCLUSIONS

Equations have been derived for use in predicting tracer flow behavior in reservoirs. The specific equations were developed to handle 5-spot flow of water tracers at a 1:1 mobility ratio. Although these conditions limit the scope of the equations; the method of approach is general enough to be used wherever areal coverage, dispersion and flow pattern is known or can be approximated.

Using the equations and the detailed tracer production history, the degree of stratification in a reservoir can be calculated.

The field test data indicate that the stratification and producing concentration values calculated from these equations are realistic, giving some confidence in the use of these equations in reservoir analysis.

ACKNOWLEDGEMENT

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NOMENCLATURE

C = Concentration (any units are permissible as long as they are consistent - generally weight fraction or ppm are used)
C_i = Peak concentration due to flow from the ith layer
C_1 = Concentration at r_1, near the midpoint L
C_o = Injected concentration
C_p = Peak concentration flowing from a homogeneous reservoir
$C(V_i)$ = Producing concentration as a function of volume injected (V_i)
F_D = Fraction of displacing fluid in the producing stream
h = Height of reservoir (ft)
h_i = Height of the ith layer (ft)
K = Dispersion coefficient for miscible displacement in a porous medium (ft^2/sec)
K_{avg} = Average permeability of the reservoir (md)
k_i = Permeability of the ith layer (md)
L = Total length of displacement, also distance from injector to producer (ft)
m = Amount of water tracer injected (lb)
PV = Effective pore volumes (dimensionless)
Q = Volumetric injection rate (ft^3/sec-ft)
Q' = $Q/2\pi\Phi$
Q_i = Location volume on the F_D curve (effective pore volumes)
r = Radius (ft)
Δr = $L-r_1$
r_1 = Radius near the tracer midpoint, L, (ft)
S_w = Water saturation (fraction)
t_1 = Time for injection of a tracer slug (sec)
t_i = Time for breakthrough of the ith layer (sec)
t_{avg} = Time for breakthrough of a homogeneous reservoir (sec)
V_i = Volume injected (effective pore volumes)
W = Width of tracer slug (ft)
α = Dispersion constant rK/Q' (ft)
Φ = Porosity (fraction)

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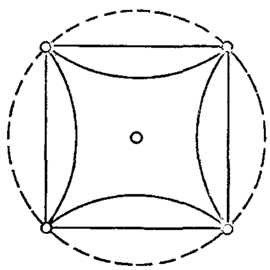


Figure 1. APPROXIMATION OF FIVE-SPOT GEOMETRY USING A CIRCLE

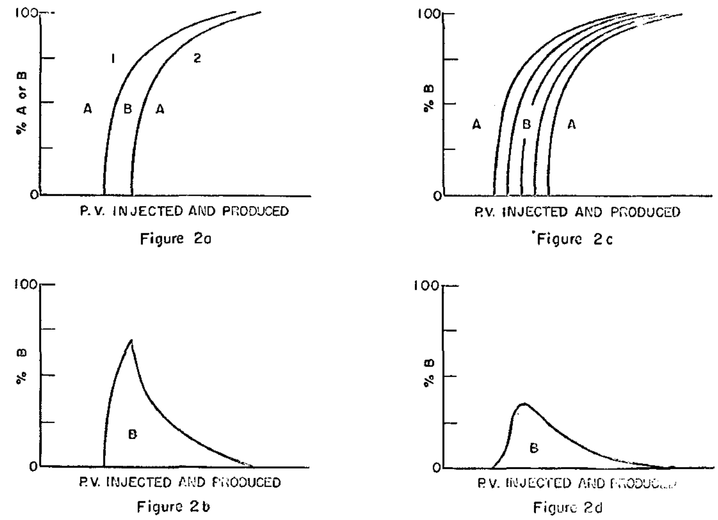


Figure 2. EFFECTS OF AREAL SWEEP ON BREAKTHROUGH

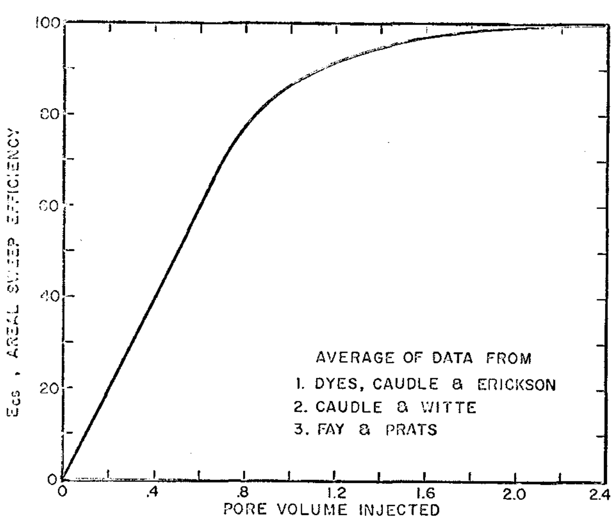


Figure 3 5-SPOT SWEEP EFFICIENCY
MOBILITY RATIO 1:1

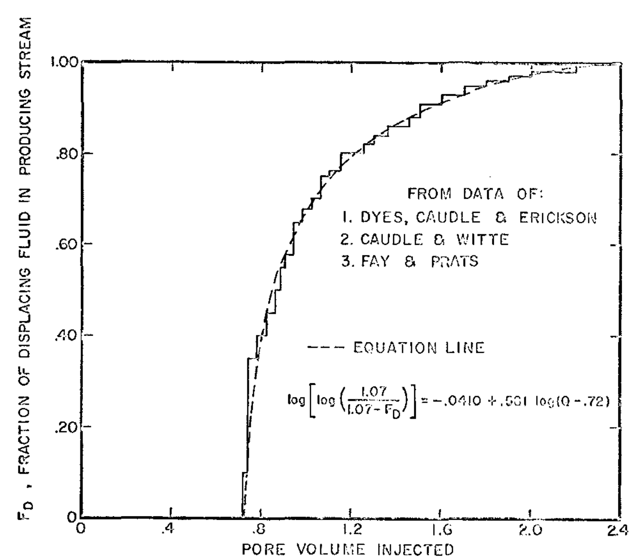


Figure 4 5-SPOT BREAKTHROUGH CURVE

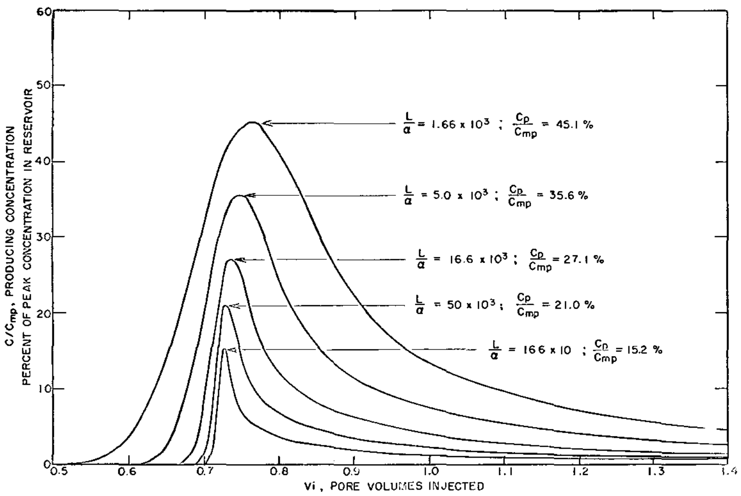


Figure 5. EFFECT OF SPACING AND DISPERSION COEFFICIENT ON BREAKTHROUGH HISTORY

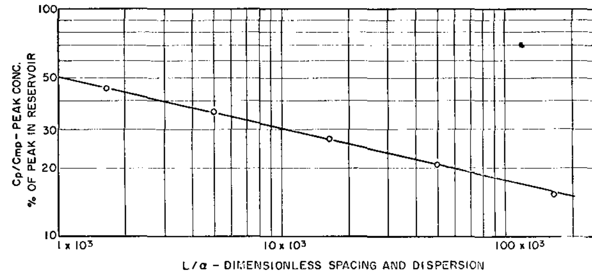
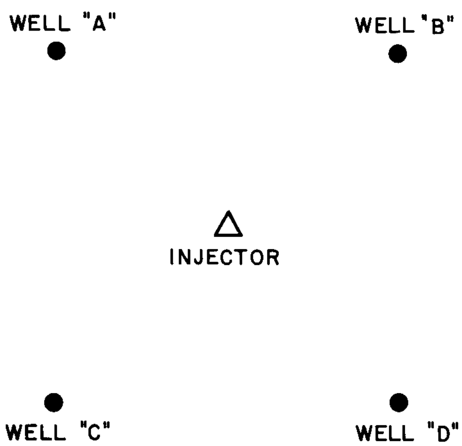


Figure 6. EFFECT OF DISPERSION AND SPACING ON PEAK PRODUCING CONCENTRATION



TRACER TEST PATTERN

Figure 7

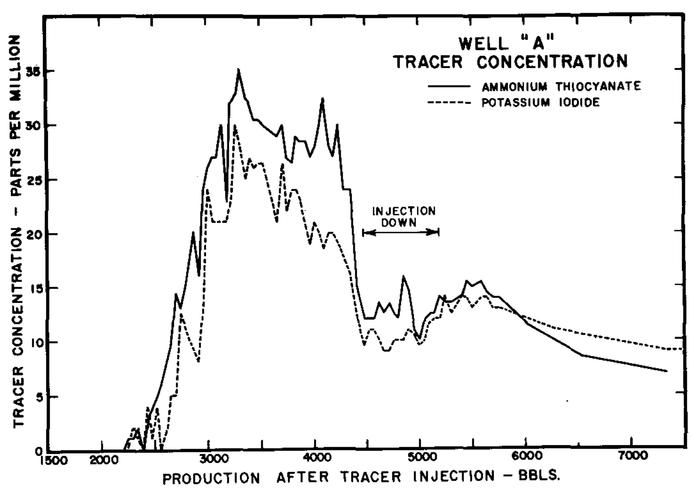


Figure 8

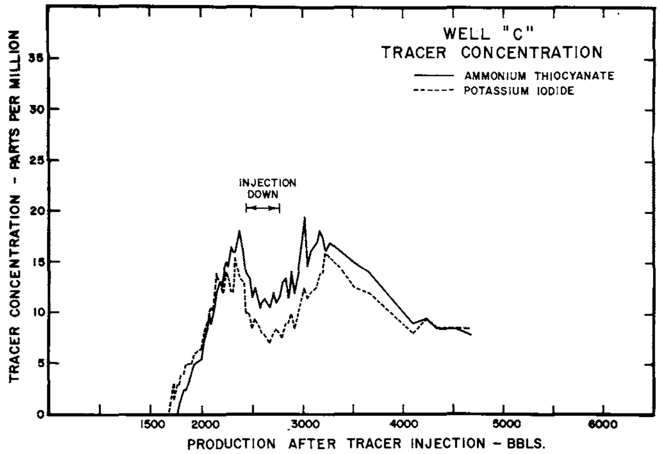


Figure 9

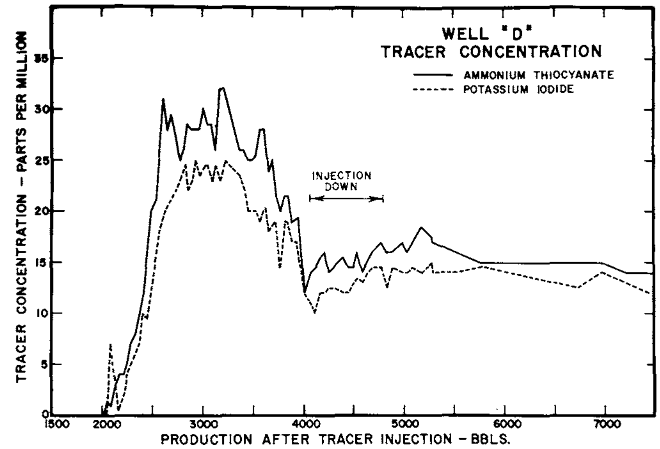


Figure 10

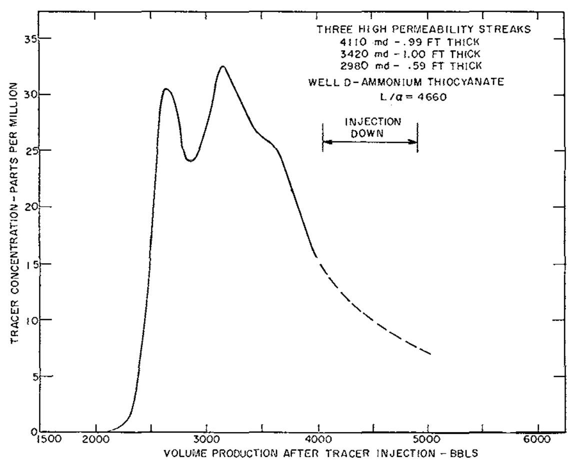


Figure 11. CALCULATED APPROXIMATION OF WELL D AMMONIUM THIOCYANATE BREAKTHROUGH CURVE