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GRAPHICAL SOLUTION OF CONCENTRATION AT PRODUCTION WELLS OF INJECTED RADIOACTIVE WATER TRACERS

BY

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A

THESIS

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ABSTRACT

With the advent of field research in which radioactive isotopes are used as tracers for water injected in secondary-recovery operations, knowledge of the probable transit time between wells of an injected tracer, its concentration at detection points, and the resultant optimum injection concentration has become important. Both detection and, consequently, injection concentrations of radioactive tracers are at least in part functions of the loss of tracer for various reasons, flow characteristics between wells, the rate of decay of radioactive emission, and the sensitivity of the detection apparatus. A method, based on the characteristics of a homogeneous 5-spot system, has been developed for predicting the approximate arrival time at a production well of any injected tracer, the injection concentration of tracer necessary to insure detectable concentration at the production well, and the optimum period of time over which the tracer should be injected.

The basic flow equation relating reservoir parameters to first arrival time of injected tracer is solved graphically. Graphs also are used to determine the frontal advance of the tracer slug along various flow paths and to locate the position of the front and rear of the tracer slug at any time after injection. Tracer concentration at the production well is expressed as the produced-volume ratio of tracer-bearing fluid to barren fluid.

Deviation of actual field concentration curves from those predicted by the described method, which assumes homogeneity, should provide information of practical value concerning reservoir heterogeneities.

INTRODUCTION

For some time it has been recognized that a need exists for a method of evaluating the transmissive characteristics of oil-productive formations and the sweep efficiencies between wells of waterflood patterns. Predictions of waterflood behavior based on wellhead or bottom-hole measurements at individual wells are subject to errors inherent to natural or artificially created fractures or other non-uniform conditions between wells. The applicability of radioactive substances as tracers for injected fluids for quantitatively and qualitatively studying transit times, injected-water distribution, and zones of greatest fluid transmission between wells has been described previously (1,2,3)[1]. Many of the results of interwell tracer tests either have been qualitative with respect to interpretation of field data or conducted under highly idealized simulated field conditions.

Quantitative evaluation of field tracer tests have been presented in the literature to a limited extent because of the complex and tedious methods of theoretical calculations required for comparing and evaluating field data (4). A theoretical method based on assumed homogeneous reservoir conditions for a 5-spot pattern is described here for determining arrival times at the production wells of any injected tracer, the necessary concentration of tracer to be injected to insure detectable concentration in the produced fluids, and the optimum time over which injection should occur. The method can be extended for use with any flooding pattern for which the pressure distribution can be deter-

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[1] Numbers in parentheses refer to items in the bibliography at the end of the paper.

mined. In respect to tracer dilution or loss, only mechanical or physical dilution is considered, with any effect of diffusion, adsorption, ion exchange, or other probable causes of tracer loss or dilution ignored for purposes of this paper.

To simplify calculations from available data, the problems involved in predicting arrival times and concentration of tracer in the produced fluids can be most conveniently approached under assumed homogeneous conditions of the reservoir and subsurface fluids, despite the fact that ideal homogeneous conditions rarely, if ever, exist in petroleum reservoirs. Considering these conditions of homogeneity, the concentration of tracer in the produced fluids will depend on: 1) The extent of dilution with barren fluid at the producing well; 2) the volume of tracer-bearing slug; and 3) the input tracer concentration. The method presented here shows the interrelation of these factors in such a way that each may be considered separately and predictions made based on the knowledge of each.

PHYSICAL AND MATHEMATICAL RELATIONSHIPS

To study the effect of permeability, saturation, porosity, well spacing, and pressure distribution on the concentration of tracer material in the produced fluids from a 5-spot pattern, it was necessary to relate these factors in an ideal, homogeneous system. This study was made following these assumptions:

1. All system and fluid properties are uniform throughout.
2. Steady-state, homogeneous fluid-flow conditions exist.
3. The one-quarter element of the 5-spot is one of a symmetrical pattern.
4. The distribution of pressure is independent of well spac-

ing and of the actual value of the pressure difference.

5. The viscosity of the injected fluid is not changed by the addition of the tracer material and is equal to the viscosity of the displaced fluids.
6. The fluid saturation remains constant.
7. The analysis is based on linear flow relation along each flow path.
8. There is no loss of tracer because of diffusion or adsorption or other possible causes in the reservoir system and the interface between the injected tracer-bearing fluid and the system fluid is vertical.
9. The input concentration of tracer is calculated at the sand face in the injection well and the output concentration is calculated upon entrance of the tracer into the production well.

From these assumed conditions, the distance of travel in any increment of time along a flow path can be calculated when the pressure distribution is known. Since the velocity of a particle traveling along any path is proportional to a function of the permeability-viscosity ratio and the pressure gradient, the increment of time for travel along increments of distance of the flow path may be expressed by the differential equation:

$$dt = \frac{u\phi}{k}\, dl\, \frac{1}{dp/dl} \text{ - - - - - - - - - - - - Equation 1}$$

Equation 1 cannot be written in a form suitable to direct solution, but an approximate solution can be obtained graphically by scaling along any flow path the distance between successive points of known pressure differentials. These scaled values can then be applied in a simplified approximation of the solution of the above equation:

$$\Delta t = \frac{u\phi}{k} \frac{(\Delta L)^2}{\Delta P} (0.158) \text{ - - - - - - - } \quad \text{Equation 2}$$

where, Δt = time for injected front advance between equipressure lines along a flow path, days.

ΔL = distance between equipressure lines along a flow path, feet.

ΔP = pressure difference between equipressure lines, p.s.i.

u = viscosity of injected and system fluids, centipoises.

k = effective permeability of medium, darcys.

ϕ = fraction of pore space occupied by moving front, porosity times saturation, fraction.

0.158 = unit conversion constant.

METHOD OF CALCULATION

The calculations for this study were performed in successive steps as follows:

1. Graphical solution of equation 2 to obtain the summation of travel times which were used to plot an instantaneous velocity curve along each flow path.
2. Calculation of the first arrival at the production well of any injected material by using the approximate solution of equation 1 along the diagonal flow path (path No. 1).
3. Plotting of the position of the injected front at any given time.

4. Calculation of the areal (unit volume) sweepout with respect to time.
5. Calculation of the ratio of tracer-bearing fluid to barren fluid produced with respect to time.
6. Calculation of a mechanical dilution factor to show the relation between the ratio of input to output concentrations of tracer material and the percent of reservoir volume injected.

Instantaneous Velocity Curves

Using the pressure distribution and flow lines shown in figure 1 (5) for a one-quarter symmetrical element of the 5-spot pattern, the increment of time for travel between each equipressure line along the indicated flow paths was calculated. This was done by graphically solving equation 2 as described herein. Values of total pressure difference of 100 p.s.i., injection well to production well distance of 100 feet, and a ratio of $u\phi/k$ of unity were assumed so that the calculations represent either percentage or unit values. The ratio of $u\phi/k = 1$ represents conditions such as fluid viscosity, 1 centipoise; porosity, 20 percent; saturation, 75 percent; and effective permeability, 150 millidarcys.

The distance between each equipressure line was scaled in feet, and the pressure differential between the equipressure lines was in p.s.i.; thus, the time required for traveling the scaled distance was calculated in days as shown in equation 2.

Figure 2 shows the instantaneous-velocity curve for each of the flow paths. These curves were obtained by plotting the summations of

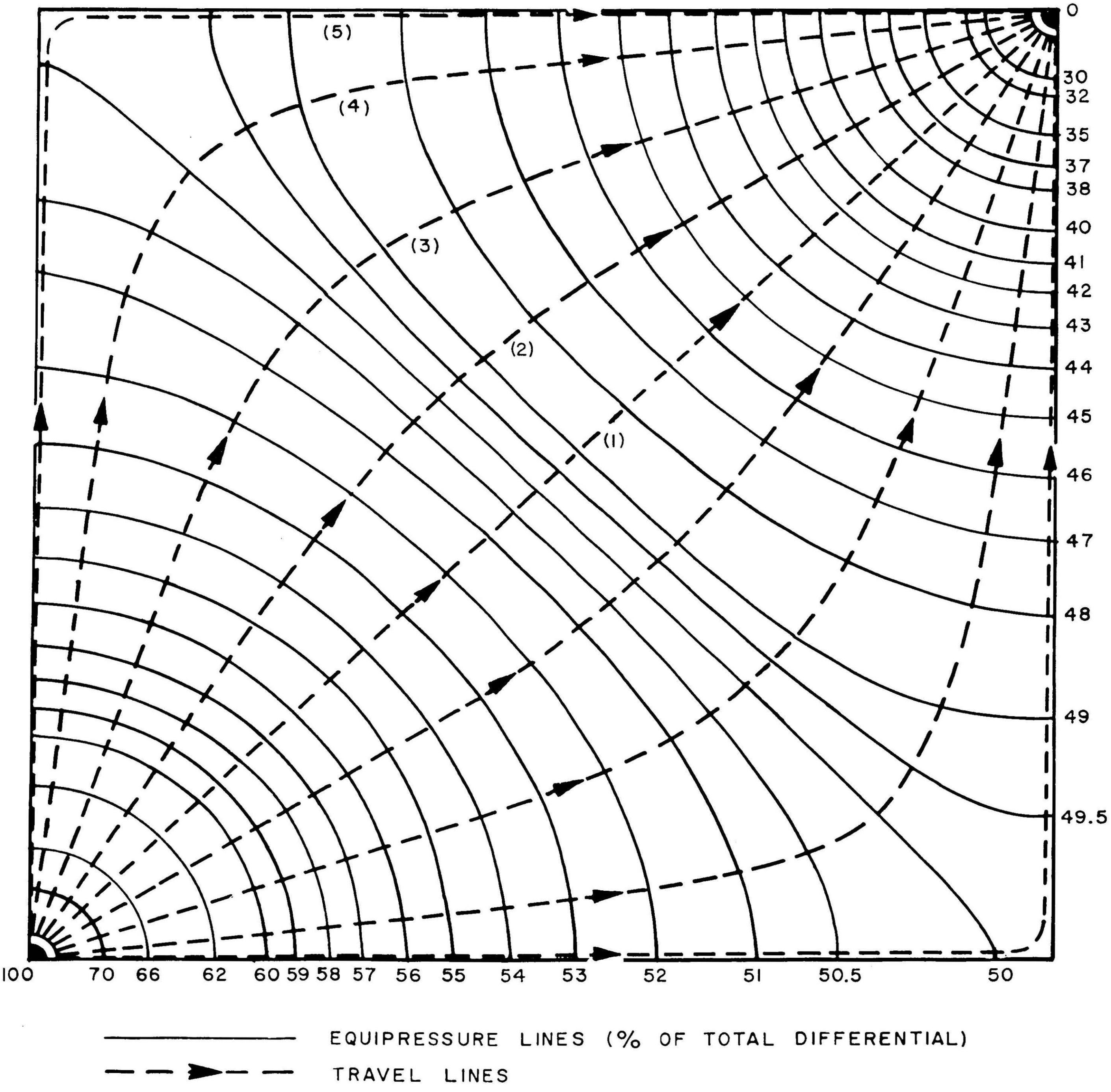

Figure 1. — Pressure-distribution and travel lines for two wells of homogeneous 5-spot pattern. [Reproduced from reference (5)].

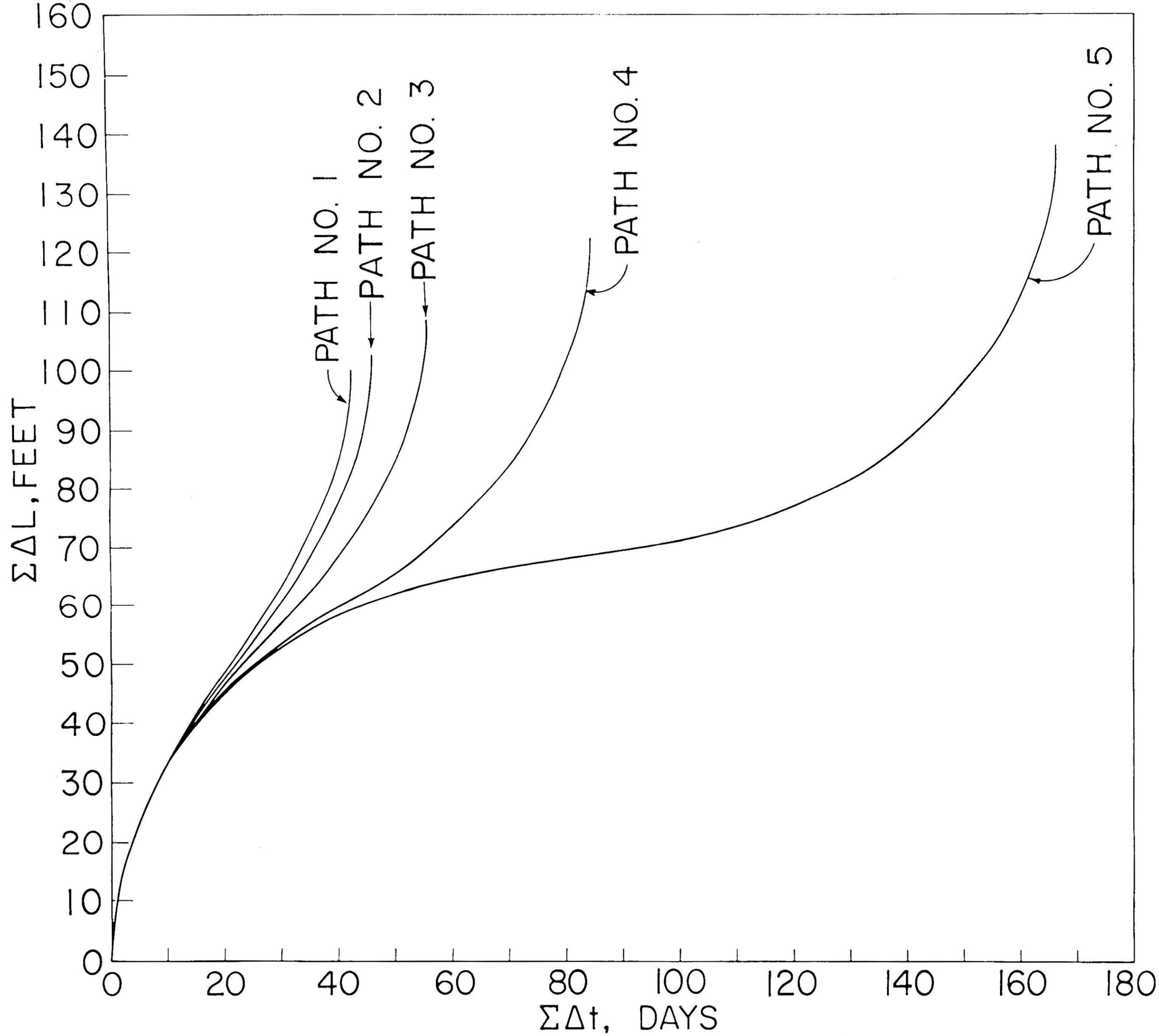

Figure 2.– Instantaneous-velocity curves for particles moving along flow paths between two wells of homogeneous 5-spot pattern.

time intervals, Δt in days, necessary for traveling the corresponding distance.

Approximate First Arrival Times

The summation of the increments of time along the diagonal flow path (No. 1) is the time of the first arrival at the production well of any injected material. The equation expressing the approximate solution of the basic equation shows that the first arrival time is directly proportional to the viscosity-permeability ratio, $u\phi/k$, and the ratio of the travel distance, ΔL, to the reciprocal of the pressure gradient, $1/dp/dl$. Using this proportionality, figure 3 was plotted to show the relation between approximate first arrival time in days, well spacing in feet, and pressure gradient in p.s.i. per foot at various viscosity-permeability ratios in centipoises per darcy. The proportionality between arrival time and the above-mentioned parameters is based on the pressure distribution given in figure 1 which accounts for the effective well radii of the system shown. In cases where the pressure distribution is not known, it has been shown that, by using a volumetric relation combined with radial flow calculations, the proportionality may be altered to include the effective well radii at the wells involved (6). The times shown in figure 3 can be changed to include the approximate effect of changes in radii of the wells by multiplying the values shown by $0.389 \log (L/2)/r_w$.

Under the assumed basic homogeneous conditions, the approximate first arrival time or "breakthrough" of any injected tracer can be determined from figure 3 if the well spacing (injection to production), total pressure difference, permeability, porosity, and fluid saturation are known.

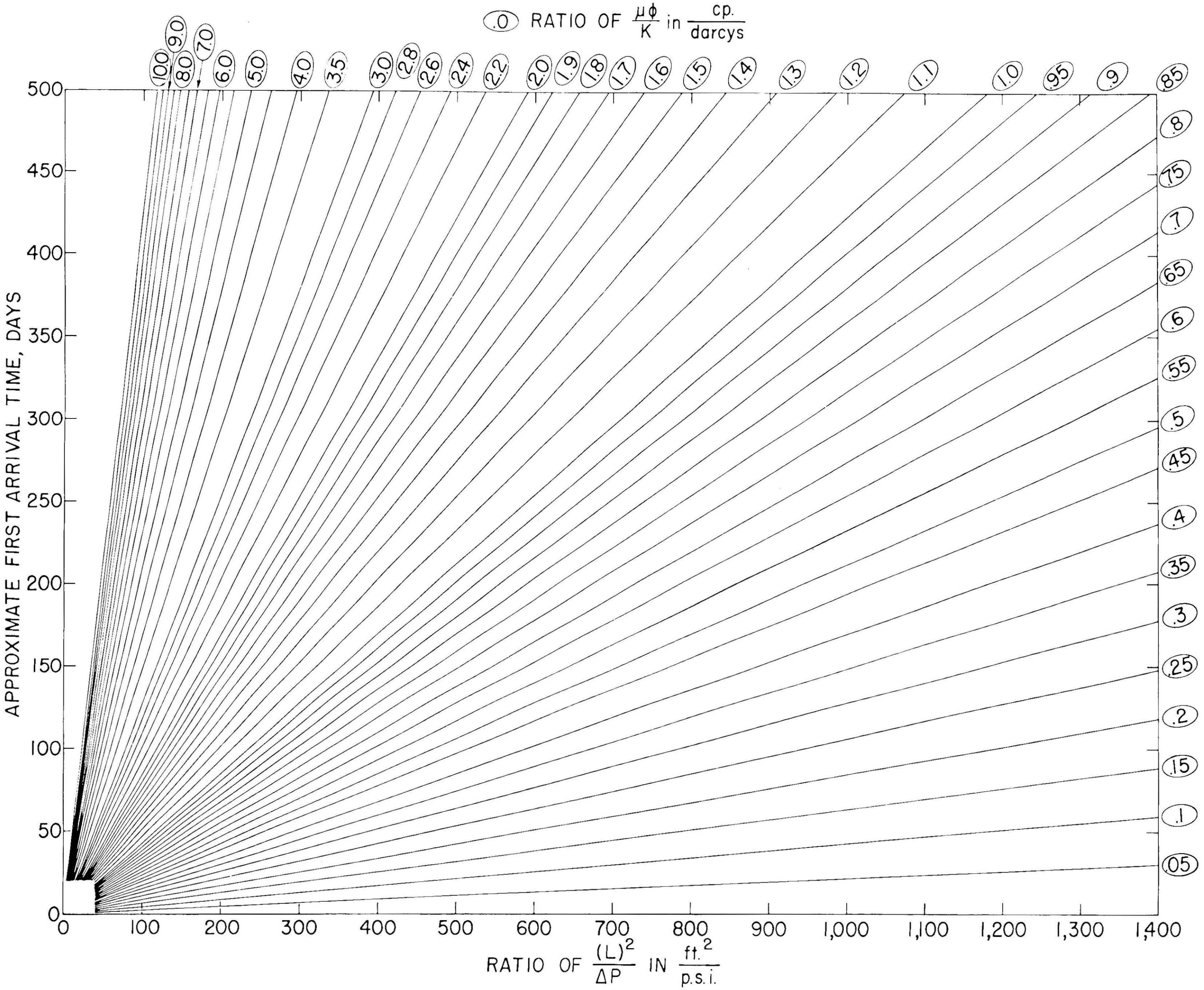

Figure 3. - Two-well graphical representation of first arrival time at production well of tracer injected into homogeneous 5-spot pattern.

Frontal Advance

Using the curves from figure 2, the traveled distance along each path was determined at equal elapsed time intervals and plotted correspondingly along the flow paths. The injection fronts shown in figure 4 were obtained by connecting distances traveled along each path in the same total elapsed time. The position of the front of injected material at various times is expressed as a percentage of the total time required for travel along path No. 5, or the percentage of total sweepout time. It is interesting to note that, for the basic assumed conditions, the ratio of the time for total sweepout to the first arrival time is constant and equals approximately 4.

Sweepout Curve

The plot of the frontal advance shown in figure 4 was used to determine the reservoir area or unit volume swept out with respect to time. The area of sweepout which is equivalent to volumetric sweepout at constant sand thickness, at various times was determined graphically and expressed as a percentage of the total area. Figure 5 shows this relation between percentage of total area swept out and percentage of time required for total sweepout.

Produced-Ratio Curves

Figure 5 makes possible volumetric calculations involving the production of a slug of tracer-bearing fluid. The position of the front and rear of the slug can be located at any given time. The area represented between the front and rear is proportional to the amount of the slug remaining in the reservoir; the difference in this area at any two times will be proportional to the amount of the slug produced dur-

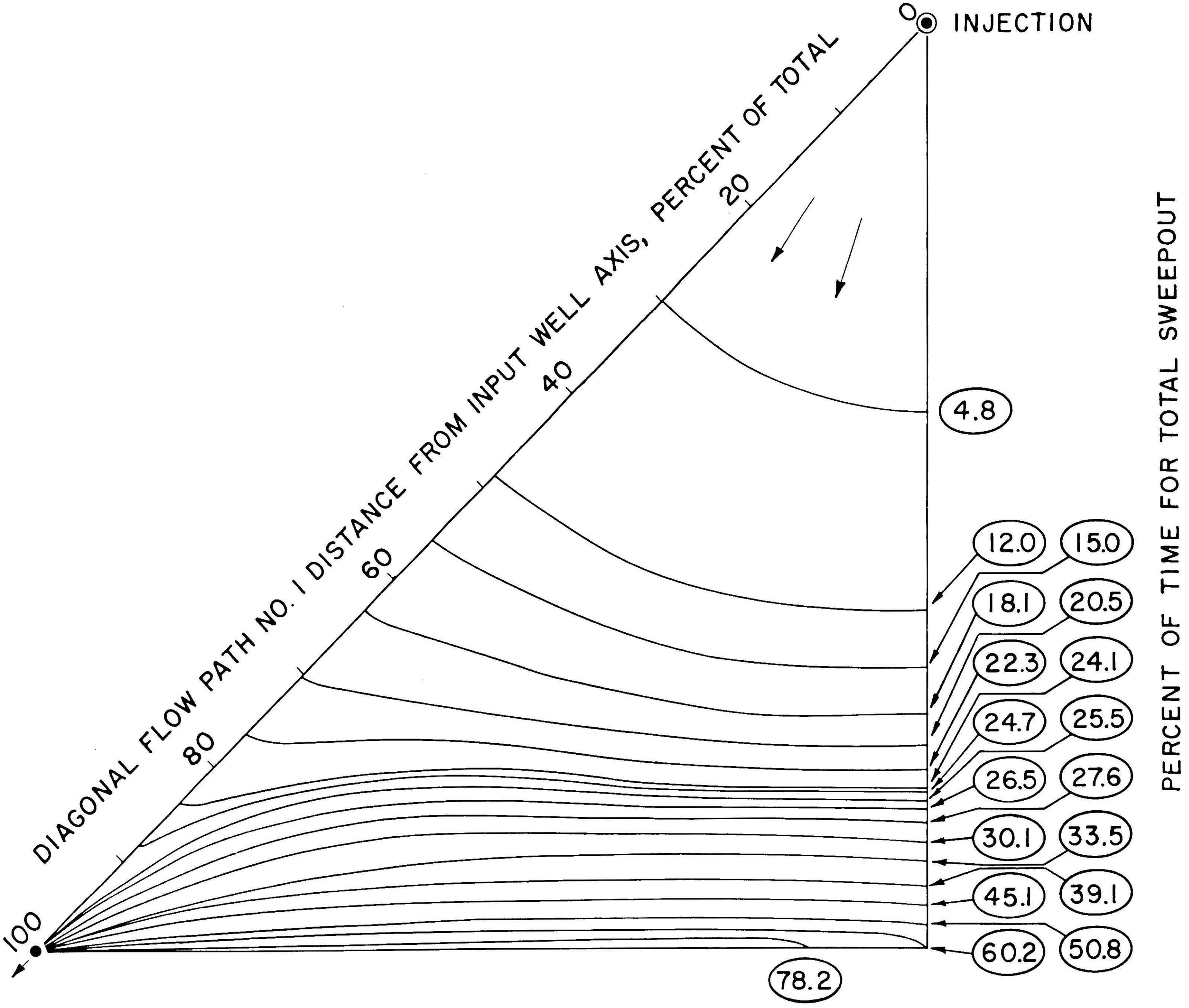

Figure 4.-Calculated positions for homogeneous element of 5-spot pattern of injection fronts of tracer slug at various times.

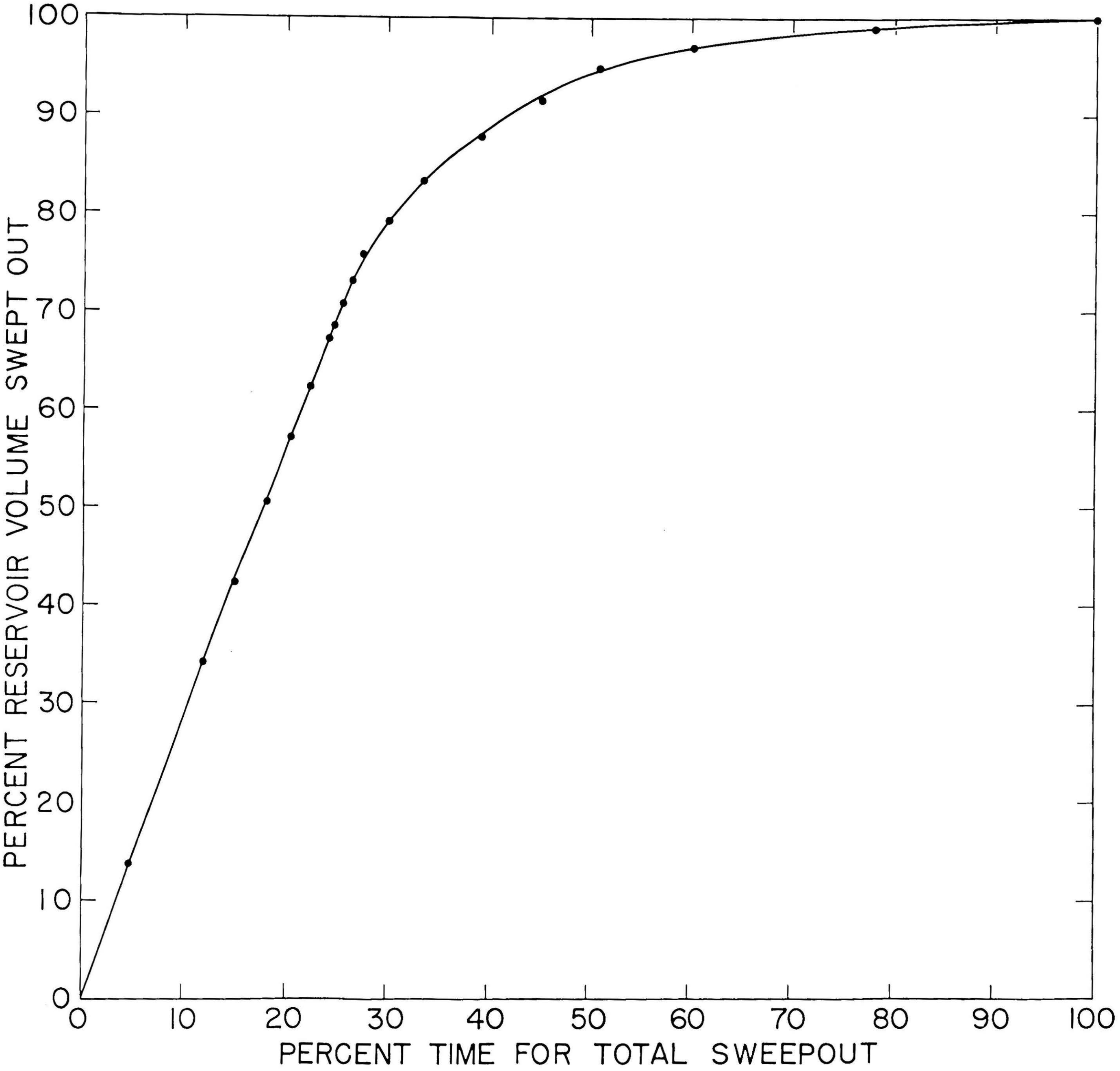

Figure 5.- Graphical determination of percentage of area or volume swept out with respect to time for homogeneous 5-spot pattern.

ing that period of time. Following the original assumptions that the fluid saturation remains unchanged, the injection of barren fluid will result in total production equal to total injection. As injection continues after the initial tracer breakthrough, the produced volume will equal the injected volume and will contain both tracer-bearing fluid and barren fluid. From this, the total produced volume during any time interval is known and the amount of tracer-bearing fluid is known; therefore, the concentration or ratio of tracer-bearing to barren fluid can be calculated.

To illustrate the above calculation, assume a uniform injection of tracer-bearing fluid equal to 10 percent of the reservoir volume available for fluid transmission followed by increments of 7.2 percent injections of barren fluid. The slug will occupy a position represented between 25.5 percent and 21.75 percent of total sweepout when the front first reaches the producer. This position can also be represented as being between 70.9 percent and 60.9 percent of total sweepout volume. At the end of the first incremental injection of barren fluid, the slug will occupy a position represented by 76.5 percent and 67.6 percent of total sweepout volume. This indicates that, during the injection of 7.2 percent reservoir volume of barren fluid, 1.1 percent of tracer-bearing, and 6.1 percent of barren fluid were produced, equal to a produced ratio of tracer-bearing to barren fluid of 0.18.

Figure 6 shows the results of this calculation for various slug volumes expressed as percentage of total reservoir volume available for injected fluid. The resulting curves show the relation of the ratio of tracer-bearing fluid to barren fluid in the produced fluids to the percentage of time required for total displacement of the slug. It

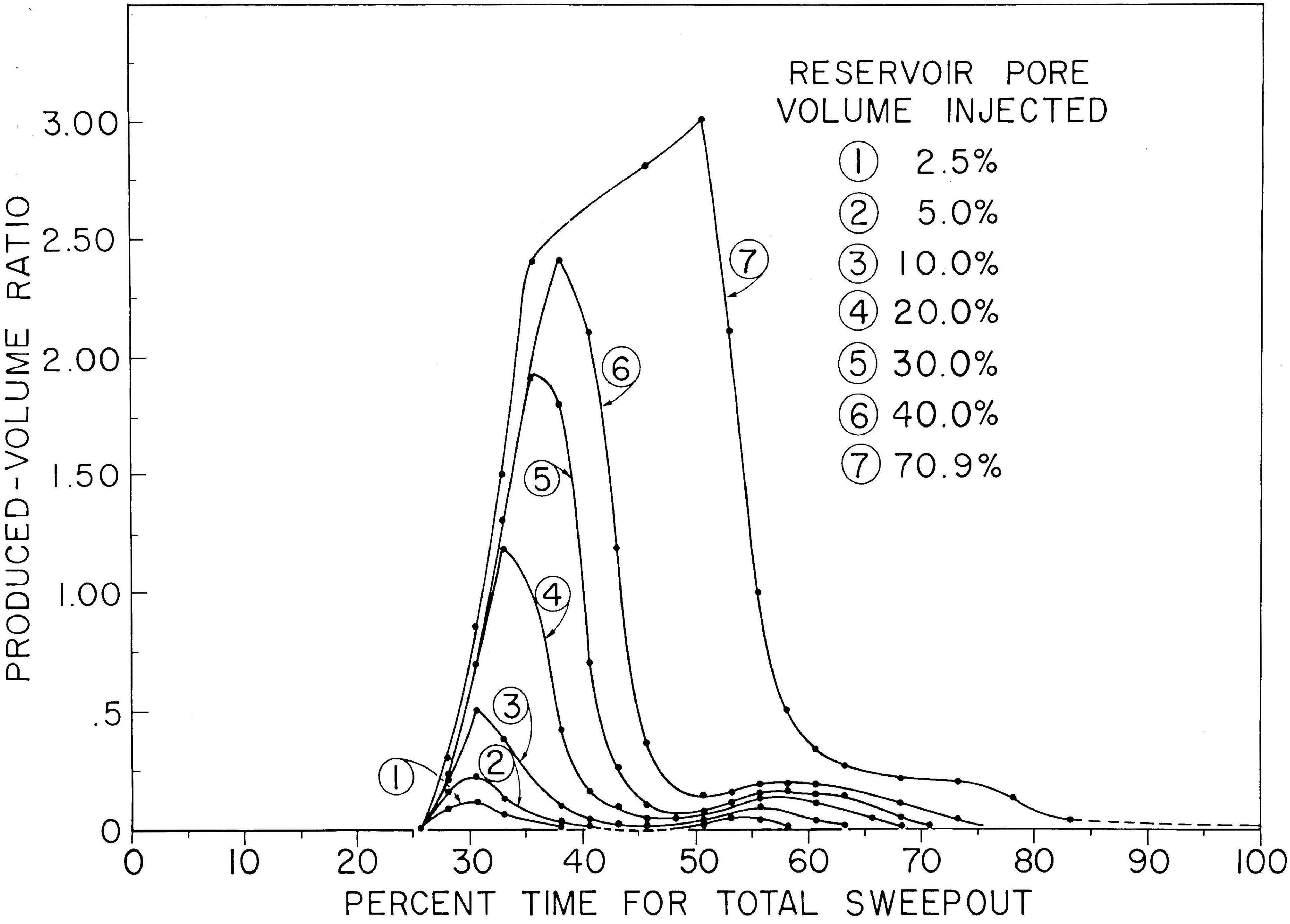

Figure 6.- Calculated produced-volume ratios of tracer-bearing fluid to barren fluid as function of percentage of time for sweepout, homogeneous 5-spot pattern.

should be noted that the ratio given in figure 6 is the ratio of tracer-bearing fluid to the barren fluid produced and is not the actual concentration of tracer in the produced fluids.

Dilution Factor Curve

Since figure 6 gives the ratio of tracer-bearing fluid to barren fluid, the ratio of tracer concentration at the injection well to the tracer concentration at the production well can be calculated for any percent reservoir pore volume injected. The injection concentration will be reduced at the production well by a factor which can be determined from figure 6, and for any reservoir pore volume injected the factor will be (Produced-Volume Ratio + 1) / (Produced-Volume Ratio). This factor is the "dilution factor" and its relation to injected concentration and output concentration is given by the following equations:

$$C_i = C_o \frac{R + 1}{R} \text{ - - - - - - - - - - - - - - - - Equation 3}$$

or,

$$\frac{C_i}{C_o} = \frac{R + 1}{R} \text{ - - - - - - - - - - - - - - - - Equation 4}$$

where, C_i = tracer concentration at the injection well.

C_o = tracer concentration at the production well.

R = Produced-Volume Ratio.

$\frac{R + 1}{R}$ = dilution factor.

Figure 7 shows the relation of the dilution factor at 80 percent of the maximum value of the Produced-Volume Ratio, R, to the percent reservoir pore space volume injected. This curve may be used to determine the injection concentration necessary for an output concentration which can be detected using devices with given sensitivities. Also, the

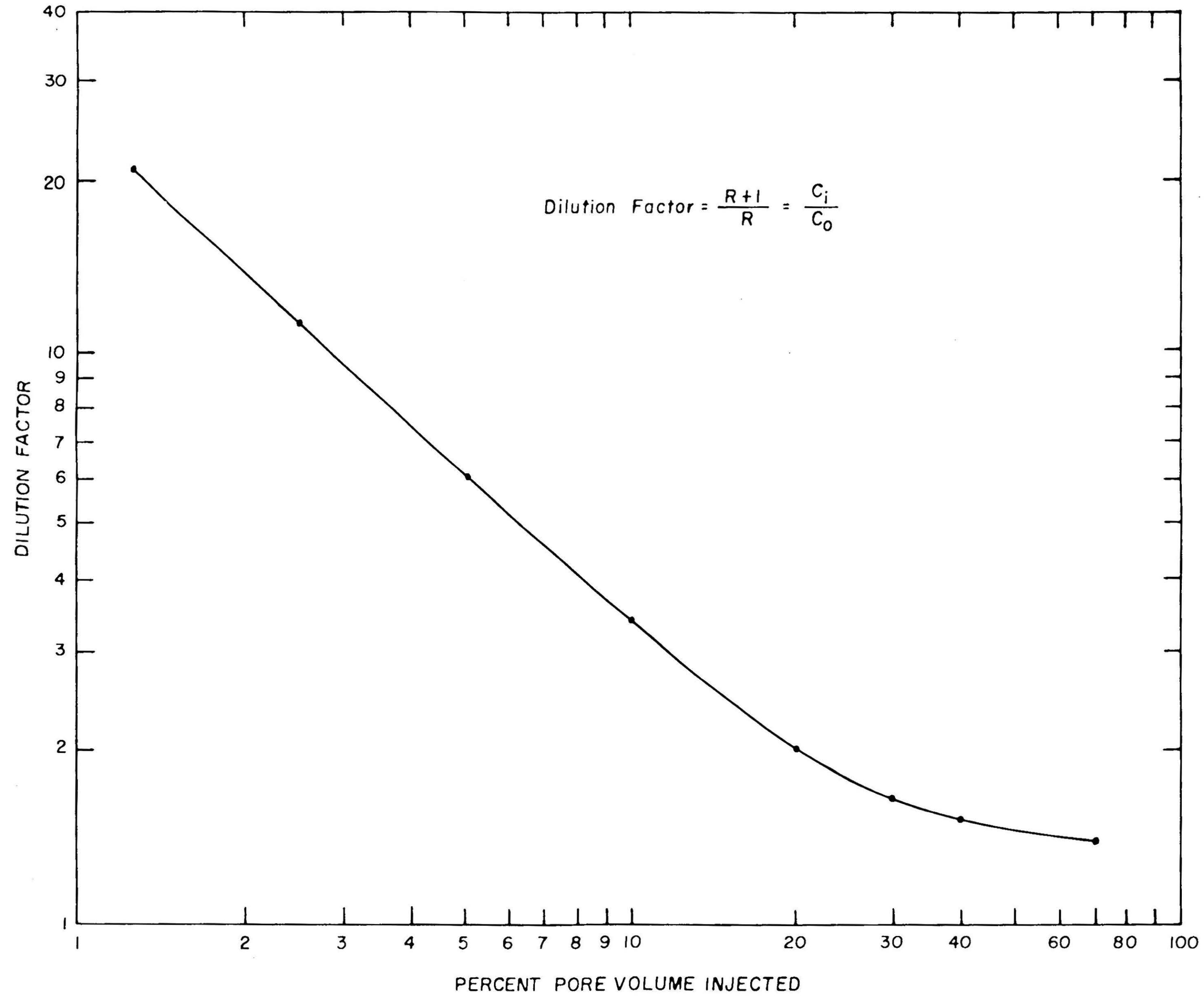

Figure 7.— Dilution factor curve for homogeneous 5-spot pattern showing relation of injected to produced concentrations at various percent of reservoir pore volume injections.

output concentration to be expected for any given input concentration can be calculated.

DISCUSSION OF APPLICATION

It is recognized that the theoretical method described in this paper has some limitations. Although many factors may contribute to the loss of a tracer substance in a porous, permeable formation, the only cause considered in the present discussion is physical dilution by water that does not bear tracer. Losses of tracer also may occur because of adsorption, ion exchange, hydrolysis and precipitation, diffusion, replacing connate water, and perhaps because of other unknown effects. Conversely, as homogeneous conditions have been assumed between wells, no allowance has been made for the effects of permeability stratification except for cases in which the thickness and permeability of such zones are known. Tracer substances usually are evaluated to determine their potential loss and are selected on the basis of expected low adsorption and ion exchange and negligible hydrolysis. If the loss of tracer from these causes is comparatively low, it is expected that the method described herein may yield a reasonable approximation of transit times and tracer dilution between wells. Obviously the method is not applicable if the tracer moves from injection wells behind pipe and into upper formations or travels through fracture systems between wells.

Although this method is based on homogeneous physical conditions, its benefits should be realized when sufficient field data are available for comparison. Assuming no tracer losses from various causes, the first arrival time and the shape of the Produced-Ratio curve will be influenced by reservoir heterogenities in such a manner that some estimate of non-uniform reservoir conditions can be made. In general, a travel time less than that predicted by theory probably will indicate channeling either through fractures or extreme permeability variations. If the time of the first arrival were greater than that predicted by this method, the indication is that the reservoir factors, probably permeability and/or fluid saturation, have been incorrectly assumed. This interpretation will be valid only if the assumption of constant saturation is true. At best, the interpretation of first arrival times is qualitative and should be used in conjunction with core analyses, well tests, and subsurface measurements.

The principal use of the arrival time curve is to determine the approximate upper limit of transit time between injection well and production well. The lapsed time between injection and detection is an important consideration when using radioactive isotopes as tracers. The isotope selected must have a decay rate such that detectable amounts will remain at the time of arrival in the production well.

It has been shown in figure 6 that the maximum concentration of tracer in the produced fluids varies with the injection volume and the time after injection. The concentration necessary for detection, as determined by the sensitivity of the detection apparatus, determines the amount of tracer to be injected, the injection time, and the time after injection that the limiting concentration will be detectable in the production well. The relation of these factors for any given situation can be determined by using figure 6 directly to calculate the dilution factor or from figure 7.

As an example of the use of the Produced-Ratio curves or the diltion factor curve, assume that a 5-spot pattern requires 50 barrels of fluid to be equivalent to 2.5 percent of the pore volume available for injected fluid and that the detecting apparatus sensitivity is such that the output concentration of a radioactive tracer should be at least 40 microcuries per barrel of produced fluid. From figure 6, the maximum produced-volume ratio obtainable from a slug volume of 2.5 percent of the total effective volume is 0.125 barrels of tracer-bearing fluid per barrel of barren fluid. Assuming the optimum time of detection will be when the produced ratio is at 80 percent of its maximum value, the produced ratio is then 0.100 barrels of tracer-bearing fluid per barrel of barren fluid. Using this ratio and the cited sensitivity of the detection apparatus, the required tracer concentration at injection can be calculated by using equation 3 to equal 288 microcuries per barrel of injected fluid, or 14.4 millicuries in the required 50 barrels of fluid. Using figure 7, the dilution factor is determined directly as 7.2, and when used in equation 4 the input concentration must be 288 microcuries per barrel of injected fluid, or 14.4 millicuries for the required 50 barrels of fluid. Knowledge of the injection rate permits injecting the tracer over the period of time necessary to inject 50 barrels of fluid. Similar calculations and predictions can be made using a combination of information derived from figure 6 or figure 7, injection and production rates, permeability profiles, or other reservoir tests.

CONCLUSIONS

The anaylsis based on homogeneous physical conditions has been shown to be potentially useful in predicting arrival times at a production well of any injected tracer and the relationship between the concentrations of injected and produced tracer. The results of a graphical solution of the basic flow equation showing the relationship between reservoir parameters and first arrival times at the production wells has been presented. These results should be useful in determining the expected arrival time at the production well of any injected tracer, selecting the proper radioactive isotope to be used as a tracer, and qualitatively interpreting relative arrival times at the various wells.

The relationship between the concentrations of injected and produced tracer, slug volume, and optimum time of detection after injection has been represented as Produced-Ratio curves and a dilution factor curve. These curves may be used in determining the optimum amount of tracer and the period of injection so that detectable concentrations will be present in the various production wells. Quantitative interpretation of actual field curves is possible through comparison with theoretical curves similar to those shown here for a 5-spot pattern. The lack of field data at present prevents any discussion of quantitative interpretation techniques other than that which can be deduced by direct comparison between field curves and theoretical curves along with other reservoir or performance data. However, it appears that deviation of actual flow patterns from those predicted by use of the described method, assuming homogeneity, may provide information of practical value regarding reservoir heterogeneities, and thereby add to the basic knowledge or understanding of reservoir mechanics.

APPENDIX

Data for Plotting Velocity Curves for Each Streamline

Path No. 1

Pressure line	ΔP p.s.i.	$\Sigma\Delta L$ scaled	$\Sigma\Delta L$ ft.	ΔL ft.	$\Delta L/\Delta P$ ft./p.s.i.	Δt days	$\Sigma\Delta t$ days
100-70	30.0	23.5	5.3	5.3	0.2	0.2	0.2
70-66	4.0	37.5	8.5	3.2	.8	.4	.6
66-62	4.0	58.0	13.2	4.7	1.2	.9	1.5
62-60	2.0	73.5	16.7	3.5	1.8	1.0	2.5
60-59	1.0	82.5	18.7	2.0	2.0	.6	3.1
59-58	1.0	92.0	20.9	2.2	2.2	.8	3.9
58-57	1.0	102.0	23.2	2.3	2.3	.8	4.7
57-56	1.0	115.0	26.2	3.0	3.0	1.4	6.1
56-55	1.0	130.0	29.6	3.4	3.4	1.8	7.9
55-54	1.0	144.0	32.8	3.2	3.2	1.6	9.5
54-53	1.0	161.0	36.6	3.8	3.8	2.3	11.8
53-52	1.0	179.5	40.8	4.2	4.2	2.8	14.6
52-51	1.0	197.0	44.8	4.0	4.0	2.5	17.1
51-50.5	.5	208.0	47.3	2.5	5.0	2.0	19.1
50.5-50	.5	218.0	49.5	2.2	4.4	1.5	20.6
50-49.5	.5	227.0	51.6	2.1	4.2	1.4	22.0
49.5-49	.5	236.0	53.6	2.0	4.0	1.3	23.3
49-48	1.0	256.0	58.2	4.6	4.6	3.3	26.6
48-47	1.0	275.0	62.5	4.3	4.3	2.9	29.5
47-46	1.0	291.5	66.2	3.7	3.7	2.2	31.7
46-45	1.0	307.5	69.8	3.6	3.6	2.0	33.7
45-44	1.0	321.5	73.0	3.2	3.2	1.6	35.3
44-43	1.0	336.0	76.3	3.3	3.3	1.7	37.0
43-42	1.0	347.5	78.9	2.6	2.6	1.1	38.1
42-41	1.0	357.5	81.2	2.3	2.3	.8	38.9
41-40	1.0	368.0	83.6	2.4	2.4	.9	39.8
40-38	2.0	381.0	86.6	3.0	1.5	.7	40.5
38-37	1.0	389.0	88.4	1.8	1.8	.5	41.0
37-35	2.0	399.5	90.8	2.4	1.2	.5	41.5
35-32	3.0	412.5	93.8	3.0	1.0	.5	42.0
32-30	2.0	418.0	95.1	1.3	.7	.1	42.1
30-0	30.0	440.0	100.0	5.0	.2	.2	42.3

Data for Plotting Velocity Curves for Each Streamline (Cont.)

Path No. 2

Pressure line	ΔP p.s.i.	$\Sigma \Delta L$ scaled	$\Sigma \Delta L$ ft.	ΔL ft.	$\Delta L / \Delta P$ ft./p.s.i.	Δt days	$\Sigma \Delta t$ days
100-70	30.0	23.5	5.3	5.3	0.2	0.2	0.2
70-66	4.0	37.5	8.5	3.2	.8	.4	.6
66-62	4.0	58.0	13.2	4.7	1.2	.9	1.5
62-60	2.0	73.5	16.7	3.5	1.8	1.0	2.5
60-59	1.0	82.5	18.7	2.0	2.0	.6	3.1
59-58	1.0	92.0	20.9	2.2	2.2	.8	3.9
58-57	1.0	102.0	23.2	2.3	2.3	.8	4.7
57-56	1.0	115.0	26.2	3.0	3.0	1.4	6.1
56-55	1.0	130.0	29.6	3.4	3.4	1.8	7.9
55-54	1.0	145.5	33.1	3.5	3.5	1.9	9.8
54-53	1.0	162.5	36.9	3.8	3.8	2.3	12.1
53-52	1.0	181.5	41.3	4.4	4.4	3.1	15.2
52-51	1.0	199.5	45.4	4.1	4.1	2.7	17.9
51-50.5	.5	212.5	48.3	2.9	5.8	2.7	20.6
50.5-50	.5	223.0	50.6	2.3	4.6	1.7	22.3
50-49.5	.5	232.0	52.7	2.1	4.2	1.4	23.7
49.5-49	.5	241.5	54.8	2.1	4.2	1.4	25.1
49-48	1.0	262.5	59.6	4.8	4.8	3.6	28.7
48-47	1.0	283.5	64.4	4.8	4.8	3.6	32.3
47-46	1.0	301.5	68.5	4.1	4.1	2.7	35.0
46-45	1.0	318.0	72.3	3.8	3.8	2.3	37.3
45-44	1.0	332.0	75.5	3.2	3.2	1.6	38.9
44-43	1.0	346.5	78.8	3.3	3.3	1.7	40.6
43-42	1.0	358.0	81.4	2.6	2.6	1.1	41.7
42-41	1.0	368.0	83.7	2.3	2.3	.8	42.5
41-40	1.0	378.5	86.1	2.4	2.4	.9	43.4
40-38	2.0	391.5	89.1	3.0	1.5	.7	44.1
38-37	1.0	399.5	90.9	1.8	1.8	.5	44.6
37-35	2.0	410.0	93.3	2.4	1.2	.5	45.1
35-32	3.0	423.0	96.3	3.0	1.0	.5	45.6
32-30	2.0	428.5	97.6	1.3	.7	.1	45.7
30-0	30.0	450.5	102.6	5.0	.2	.2	45.9

Data for Plotting Velocity Curves for Each Streamline (Cont.)

Path No. 3

Pressure line	ΔP p.s.i.	$\Sigma\Delta L$ scaled	$\Sigma\Delta L$ ft.	ΔL ft.	$\Delta L / \Delta P$ ft./p.s.i.	Δt days	$\Sigma\Delta t$ days
100-70	30.0	23.5	5.3	5.3	0.2	0.2	0.2
70-66	4.0	37.5	8.5	3.2	.8	.4	.6
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62-60	2.0	73.5	16.7	3.5	1.8	1.0	2.5
60-59	1.0	82.5	18.7	2.0	2.0	.6	3.1
59-58	1.0	92.0	20.9	2.2	2.2	.8	3.9
58-57	1.0	102.0	23.2	2.3	2.3	.8	4.7
57-56	1.0	115.0	26.2	3.0	3.0	1.4	6.1
56-55	1.0	130.0	29.6	3.4	3.4	1.8	7.9
55-54	1.0	146.0	33.2	3.6	3.6	2.0	9.9
54-53	1.0	165.0	37.5	4.3	4.3	2.9	12.8
53-52	1.0	186.5	42.4	4.9	4.9	3.8	16.6
52-51	1.0	206.5	47.0	4.6	4.6	3.3	19.9
51-50.5	.5	223.5	50.8	3.8	7.6	4.6	24.5
50.5-50	.5	236.5	53.7	2.9	5.8	2.7	27.2
50-49.5	.5	248.0	56.4	2.7	5.4	2.3	29.5
49.5-49	.5	259.0	58.9	2.4	4.8	2.0	31.5
49-48	1.0	284.5	64.7	5.8	5.8	5.3	36.8
48-47	1.0	307.5	69.8	5.1	5.1	4.1	40.9
47-46	1.0	328.0	74.5	4.7	4.7	3.5	44.4
46-45	1.0	346.0	78.6	4.1	4.1	2.7	47.1
45-44	1.0	360.0	81.8	3.2	3.2	1.6	48.7
44-43	1.0	374.5	85.1	3.3	3.3	1.7	50.4
43-42	1.0	386.0	87.7	2.6	2.6	1.1	51.5
42-41	1.0	396.0	90.0	2.3	2.3	.8	52.3
41-40	1.0	406.5	92.4	2.4	2.4	.9	53.2
40-38	2.0	419.5	95.4	3.0	1.5	.7	53.9
38-37	1.0	427.5	97.2	1.8	1.8	.5	54.4
37-35	2.0	438.0	99.6	2.4	1.2	.5	54.9
35-32	3.0	451.0	102.6	3.0	1.0	.5	55.4
32-30	2.0	456.5	103.9	1.3	.7	.1	55.5
30-0	30.0	478.5	108.9	5.0	.2	.2	55.7

Data for Plotting Velocity Curves for Each Streamline (Cont.)

Path No. 4

Pressure line	ΔP p.s.i.	$\Sigma\Delta L$ scaled	$\Sigma\Delta L$ ft.	ΔL ft.	$\Delta L/\Delta P$ ft./p.s.i.	Δt days	$\Sigma\Delta t$ days
100-70	30.0	23.5	5.3	5.3	0.2	0.2	0.2
70-66	4.0	37.5	8.5	3.2	.8	.4	.6
66-62	4.0	58.0	13.2	4.7	1.2	.9	1.5
62-60	2.0	73.5	16.7	3.5	1.8	1.0	2.5
60-59	1.0	82.5	18.7	2.0	2.0	.6	3.1
59-58	1.0	92.0	20.9	2.2	2.2	.8	3.9
58-57	1.0	102.0	23.2	2.3	2.3	.8	4.7
57-56	1.0	115.0	26.2	3.0	3.0	1.4	6.1
56-55	1.0	130.0	29.6	3.4	3.4	1.8	7.9
55-54	1.0	146.0	33.2	3.6	3.6	2.0	9.9
54-53	1.0	167.0	38.0	4.8	4.8	3.6	13.5
53-52	1.0	191.0	43.4	5.4	5.4	4.6	18.1
52-51	1.0	218.0	49.6	6.2	6.2	6.1	24.2
51-50.5	.5	240.0	54.6	5.0	10.0	7.9	32.1
50.5-50	.5	263.0	59.8	5.2	10.4	8.5	40.6
50-49.5	.5	285.0	64.8	5.0	10.0	7.9	48.5
49.5-49	.5	303.0	68.9	4.1	8.2	5.3	53.8
49-48	1.0	337.0	76.6	7.7	7.7	9.4	63.2
48-47	1.0	363.0	82.5	5.9	5.9	5.5	68.7
47-46	1.0	385.0	87.5	5.0	5.0	3.9	72.6
46-45	1.0	404.0	92.0	4.5	4.5	3.2	75.8
45-44	1.0	418.0	95.2	3.2	3.2	1.6	77.4
44-43	1.0	432.4	98.5	3.3	3.3	1.7	79.1
43-42	1.0	444.0	101.1	2.6	2.6	1.1	80.2
42-41	1.0	454.0	103.4	2.3	2.3	.8	81.0
41-40	1.0	464.5	105.8	2.4	2.4	.9	81.9
40-38	2.0	477.5	108.8	3.0	3.0	.7	82.6
38-37	1.0	485.5	110.6	1.8	1.8	.5	83.1
37-35	2.0	496.0	113.0	2.4	1.2	.5	83.6
35-32	3.0	509.0	116.0	3.0	1.0	.5	84.1
32-30	2.0	514.5	117.3	1.3	.7	.1	84.2
30-0	30.0	536.5	122.3	5.0	.2	.2	84.4

Data for Plotting Velocity Curves for Each Streamline (Cont.)

Path No. 5

Pressure line	ΔP p.s.i.	$\Sigma \Delta L$ scaled	$\Sigma \Delta L$ ft.	ΔL ft.	$\Delta L / \Delta P$ ft./p.s.i.	Δt days	$\Sigma \Delta t$ days
100-70	30.0	23.5	5.3	5.3	0.2	0.2	0.2
70-66	4.0	37.5	8.5	3.2	.8	.4	.6
66-62	4.0	58.0	13.2	4.7	1.2	.9	1.5
62-60	2.0	73.5	16.7	3.5	1.8	1.0	2.5
60-59	1.0	82.5	18.7	2.0	2.0	.6	3.1
59-58	1.0	92.0	20.9	2.2	2.2	.8	3.9
58-57	1.0	102.0	23.2	2.3	2.3	.8	4.7
57-56	1.0	115.0	26.2	3.0	3.0	1.4	6.1
56-55	1.0	130.0	29.6	3.4	3.4	1.8	7.9
55-54	1.0	146.0	33.2	3.6	3.6	2.0	9.9
54-53	1.0	167.0	38.0	4.8	4.8	3.6	13.5
53-52	1.0	192.0	43.6	5.6	5.6	4.9	18.4
52-51	1.0	222.5	50.6	7.0	7.0	7.7	26.1
51-50.5	.5	246.0	55.9	5.3	10.6	8.9	35.0
50.5-50	.5	291.0	66.2	10.3	20.6	33.6	68.6
50-49.5	.5	351.0	79.7	13.5	27.0	57.5	126.1
49.5-49	.5	375.5	85.4	5.7	11.4	10.3	136.4
49-48	1.0	409.0	93.0	7.6	7.6	9.1	145.5
48-47	1.0	435.5	99.0	6.0	6.0	5.7	151.2
47-46	1.0	457.5	104.0	5.0	5.0	3.9	155.1
46-45	1.0	476.5	108.0	4.0	4.0	2.5	157.6
45-44	1.0	490.5	111.2	3.2	3.2	1.6	159.2
44-43	1.0	505.0	114.5	3.3	3.3	1.7	160.9
43-42	1.0	516.5	117.1	2.6	2.6	1.1	162.0
42-41	1.0	526.5	119.4	2.3	2.3	.8	162.8
41-40	1.0	537.0	121.8	2.4	2.4	.9	163.7
40-38	2.0	550.0	124.8	3.0	1.5	.7	164.4
38-37	1.0	558.0	126.6	1.8	1.8	.5	164.9
37-35	2.0	568.5	129.0	2.4	1.2	.5	165.4
35-32	3.0	581.5	132.0	3.0	1.0	.5	165.9
32-30	2.0	587.0	133.3	1.3	.7	.1	166.0
30-0	30.0	609.0	138.3	5.0	.2	.2	166.2

Data for Plotting Fluid Fronts (Taken from $\Sigma\Delta L - \Sigma\Delta t$ curves)

Travel paths	No. 1	No. 2	No. 3	No. 4	No. 5
$\Sigma\Delta t$ days	$\Sigma\Delta L$ ft.	$\Sigma\Delta L$ ft.	$\Sigma\Delta L$ ft.	$\Sigma\Delta L$ ft.	$\Sigma\Delta L$ ft.
7.9	29.6	29.6	29.6	29.6	29.6
20.0	48.8	48.0	46.7	45.3	45.1
25.0	55.8	54.0	52.0	49.8	49.3
30.0	63.4	60.7	57.0	53.6	52.8
34.0	70.6	66.6	61.2	56.2	55.3
37.0	76.6	71.7	64.6	58.2	57.0
40.0	84.2	77.4	68.4	60.0	58.5
41.0	88.6	79.6	69.8	60.4	58.8
42.3	100.0	83.0	71.7	61.2	59.5
44.0		87.9	74.0	62.0	60.2
45.9		102.6	77.0	63.2	60.9
50.0			84.4	65.6	62.3
55.7			108.9	69.9	63.9
65.0				78.3	65.8
75.0				91.0	67.4
84.4				122.3	68.8
100.0					71.1
130.0					80.6
166.2					138.3

Data for Plotting Sweepout Curve

Front	Total Area scaled	Swept Area scaled	Swept Area %	Time days	Total Time 100%	Time %
1	194,688	26,857	13.8	7.9	166.2	4.8
2	Do	66,655	34.2	20.0	Do	12.0
3	Do	82,551	42.4	25.0	Do	15.0
4	Do	98,448	50.6	30.0	Do	18.1
5	Do	111,350	57.2	34.0	Do	20.5
6	Do	121,561	62.4	37.0	Do	22.3
7	Do	130,992	67.3	40.0	Do	24.1
8	Do	133,596	68.6	41.0	Do	24.7
9	Do	138,028	70.9	42.3	Do	25.5
10	Do	142,487	73.2	44.0	Do	26.5
11	Do	147,733	75.9	45.9	Do	27.6
12	Do	154,364	79.3	50.0	Do	30.1
13	Do	163,333	83.9	55.7	Do	33.5
14	Do	170,751	87.7	65.0	Do	39.1
15	Do	177,557	91.2	75.0	Do	45.1
16	Do	184,819	94.9	84.4	Do	50.8
17	Do	188,805	97.0	100.0	Do	60.2
18	Do	192,565	98.9	130.0	Do	78.2
19	Do	194,688	100.0	166.2	Do	100.0

Data for Plotting Produced-Volume Ratio Curves

Volume Injection = 2.5%

Front time	Front	Rear time	Rear	Difference	Tracer prod.	Total prod.	Water prod.	Ratio
25.5	70.9	24.6	68.4	2.5	0.	7.2	7.2	0.
28.0	76.5	27.1	74.5	2.0	.5	7.2	6.7	.07
30.5	80.4	29.6	79.1	1.3	.7	7.2	6.5	.11
33.0	83.2	32.1	82.2	1.0	.3	7.2	6.9	.04
35.5	85.2	34.6	84.4	.8	.2	7.2	7.0	.03
38.0	86.9	37.1	86.2	.7	.1	7.2	7.2	.01

Volume Injection = 5%

25.5	70.9	23.7	65.9	5.0	0.	7.2	7.2	0.
28.0	76.5	26.2	72.5	4.0	1.0	7.2	6.2	.16
30.5	80.4	28.7	77.7	2.7	1.3	7.2	5.9	.22
33.0	83.2	31.2	81.2	2.0	.7	7.2	6.5	.11
35.5	85.2	33.7	83.7	1.5	.5	7.2	6.7	.07
38.0	86.9	36.2	85.6	1.3	.2	7.2	7.0	.03
40.5	88.6	38.7	87.4	1.2	.1	7.2	7.1	.01
43.0	90.2	41.2	89.0	1.2	0.	7.2	7.2	0.
45.5	91.7	43.7	90.5	1.2	0.	7.2	7.2	0.
48.0	93.2	46.2	92.0	1.2	0.	7.2	7.2	0.
50.5	94.5	48.7	93.4	1.1	.1	7.2	7.1	.01
53.0	95.5	51.2	94.7	.8	.3	7.2	6.9	.04
55.5	96.1	53.7	95.5	.6	.2	7.2	7.0	.03
58.0	96.6	56.2	96.2	.5	.1	7.2	7.1	.01

Data for Plotting Produced-Volume Ratio Curves (Cont.)

Volume Injection = 10%

Front time	Front	Rear time	Rear	Difference	Tracer prod.	Total prod.	Water prod.	Ratio
25.5	70.9	21.8	60.9	10.0	0.	7.2	7.2	0.
28.0	76.5	24.3	67.6	8.9	1.1	7.2	6.1	.18
30.5	80.4	26.8	73.9	6.5	2.4	7.2	4.8	.50
33.0	83.2	29.3	78.7	4.5	2.0	7.2	5.2	.38
35.5	85.2	31.8	81.9	3.3	1.2	7.2	6.0	.20
38.0	86.9	34.3	84.2	2.7	.6	7.2	6.6	.09
40.5	88.6	36.8	86.1	2.5	.2	7.2	7.0	.03
43.0	90.2	39.3	87.8	2.4	.1	7.2	7.1	.01
45.5	91.7	41.8	89.4	2.3	.1	7.2	7.1	.01
48.0	93.2	44.3	91.0	2.2	.1	7.2	7.1	.01
50.5	94.5	46.8	92.5	2.0	.2	7.2	7.0	.03
53.0	95.5	49.3	93.9	1.6	.4	7.2	6.8	.06
55.5	96.1	51.8	95.1	1.0	.6	7.2	6.6	.09
58.0	96.6	54.3	95.9	.7	.3	7.2	6.9	.04
60.5	97.0	56.8	96.5	.5	.2	7.2	7.0	.03
63.0	97.3	59.3	96.9	.4	.1	7.2	7.1	.01

Volume Injection = 20%

25.5	70.9	18.1	50.9	20.0	0.	7.2	7.2	0.
28.0	76.5	20.6	57.6	18.9	1.1	7.2	6.1	.18
30.5	80.4	23.1	64.4	16.0	2.9	7.2	4.3	.68
33.0	83.2	25.6	71.1	12.1	3.9	7.2	3.3	1.18
35.5	85.2	28.1	76.7	8.5	3.6	7.2	3.6	1.00
38.0	86.9	30.6	80.5	6.4	2.1	7.2	5.1	.41
40.5	88.6	33.1	83.1	5.5	.9	7.2	6.3	.14
43.0	90.2	35.6	85.3	4.9	.6	7.2	6.6	.09
45.5	91.7	38.1	87.0	4.7	.2	7.2	7.0	.03
48.0	93.2	40.6	88.7	4.5	.2	7.2	7.0	.03
50.5	94.5	43.1	90.3	4.2	.3	7.2	6.9	.04
53.0	95.5	45.6	91.8	3.7	.5	7.2	6.7	.07
55.5	96.1	48.1	93.3	2.8	.9	7.2	6.3	.14
58.0	96.6	50.6	94.6	2.0	.8	7.2	6.4	.13
60.5	97.0	53.1	95.6	1.4	.6	7.2	6.6	.09
63.0	97.3	55.6	96.2	1.1	.3	7.2	6.9	.04
65.5	97.6	58.1	96.7	.9	.2	7.2	7.0	.03
68.0	97.9	60.6	97.1	.8	.1	7.2	7.1	.01

Data for Plotting Produced-Volume Ratio Curves (Cont.)

Volume Injection = 30%

Front time	Front	Rear time	Rear	Difference	Tracer prod.	Total prod.	Water prod.	Ratio
25.5	70.9	14.4	40.9	30.0	0.	7.2	7.2	0.
28.0	76.5	16.9	47.6	28.9	1.1	7.2	6.1	.18
30.5	80.4	19.4	54.4	26.0	2.9	7.2	4.3	.68
33.0	83.2	21.9	61.2	22.0	4.0	7.2	3.2	1.30
35.5	85.2	24.4	67.9	17.3	4.7	7.2	2.5	1.90
38.0	86.9	26.9	74.2	12.7	4.6	7.2	2.6	1.80
40.5	88.6	29.4	78.9	9.7	3.0	7.2	4.2	.72
43.0	90.2	31.9	82.0	8.2	1.5	7.2	5.7	.26
45.5	91.7	34.4	84.3	7.4	.6	7.2	6.6	.09
48.0	93.2	36.9	86.2	7.0	.4	7.2	6.8	.06
50.5	94.5	39.4	87.9	6.6	.4	7.2	6.8	.06
53.0	95.5	41.9	89.5	6.0	.6	7.2	6.6	.09
55.5	96.1	44.4	91.1	5.0	1.0	7.2	6.2	.16
58.0	96.6	46.9	92.6	4.0	1.0	7.2	6.2	.16
60.5	97.0	49.4	93.9	3.1	.9	7.2	6.3	.14
63.0	97.3	51.9	95.0	2.3	.8	7.2	6.4	.13
65.5	97.6	54.4	96.0	1.6	.7	7.2	6.5	.11
68.0	97.9	56.9	96.6	1.3	.3	7.2	7.0	.04
70.5	98.2	59.4	97.0	1.2	.1	7.2	7.1	.01

Volume Injection = 40%

25.5	70.9	10.8	30.9	40.0	0.	7.2	7.2	0.
28.0	76.5	13.3	37.8	38.7	1.3	7.2	5.9	.22
30.5	80.4	15.8	44.6	35.8	2.9	7.2	4.3	.68
33.0	83.2	18.3	51.5	31.7	4.1	7.2	3.1	1.30
35.5	85.2	20.8	58.2	27.0	4.7	7.2	2.5	1.90
38.0	86.9	23.3	65.0	21.9	5.1	7.2	2.1	2.40
40.5	88.6	25.8	71.6	17.0	4.9	7.2	2.3	2.10
43.0	90.2	28.3	77.1	13.1	3.9	7.2	3.3	1.18
45.5	91.7	30.8	80.8	10.9	2.2	7.2	6.0	.36
48.0	93.2	33.3	83.3	9.9	1.0	7.2	6.2	.16
50.5	94.5	35.8	85.4	9.1	.9	7.2	6.3	.14
53.0	95.5	38.3	87.1	8.4	.7	7.2	6.5	.11
55.5	96.1	40.8	88.8	7.3	1.1	7.2	6.1	.18
58.0	96.6	43.3	90.4	6.2	1.1	7.2	6.1	.18
60.5	97.0	45.8	91.9	5.1	1.1	7.2	6.1	.18
63.0	97.3	48.3	93.4	3.9	1.2	7.2	6.0	.20
65.5	97.6	50.8	94.6	3.0	.9	7.2	6.3	.14
68.0	97.9	53.3	95.6	2.3	.7	7.2	6.5	.11
70.5	98.2	55.8	96.2	2.0	.3	7.2	6.9	.04
73.0	98.5	58.3	96.7	1.8	.2	7.2	7.0	.03
75.5	98.7	60.8	97.1	1.6	.1	7.2	7.1	.01

Data for Plotting Produced-Volume Ratio Curves (Cont.)

Volume Injection = 70.9%

Front time	Front	Rear time	Read	Difference	Tracer prod.	Total prod.	Water prod.	Ratio
25.5	70.9	0.	0.	70.9	0.	7.2	0.	0.
28.0	76.5	2.5	7.2	69.3	1.6	7.2	5.6	.29
30.5	80.4	5.0	14.4	66.0	3.3	7.2	3.9	.85
33.0	83.2	7.5	21.5	61.7	4.3	7.2	2.9	1.50
35.5	85.2	10.0	28.6	56.6	5.1	7.2	2.1	2.40
38.0	86.9	12.5	35.5	51.4	5.2	7.2	2.0	2.65
40.5	88.6	15.0	42.4	46.2	5.2	7.2	2.0	2.66
43.0	90.2	17.5	49.3	40.9	5.3	7.2	1.9	2.87
45.5	91.7	20.0	56.1	35.6	5.3	7.2	1.9	2.88
48.0	93.2	22.5	62.9	30.3	5.3	7.2	1.9	2.89
50.5	94.5	25.0	69.6	24.9	5.4	7.2	1.8	3.00
53.0	95.5	27.5	75.5	20.0	4.9	7.2	2.3	2.10
55.5	96.1	30.0	79.7	16.4	3.6	7.2	3.6	1.00
58.0	96.6	32.5	82.6	14.0	2.4	7.2	4.8	.50
60.5	97.0	35.0	84.8	12.2	1.8	7.2	5.4	.33
63.0	97.3	37.5	86.6	10.7	1.5	7.2	5.7	.26
65.5	97.6	40.0	88.3	9.3	1.4	7.2	5.8	.24
68.0	97.9	42.5	89.9	8.0	1.3	7.2	5.9	.22
70.5	98.2	45.0	91.4	6.8	1.2	7.2	6.0	.20
73.0	98.5	47.5	92.9	5.6	1.2	7.2	6.0	.20
75.5	98.7	50.0	94.2	4.5	1.1	7.2	6.1	.18
78.0	98.9	52.5	95.2	3.7	.8	7.2	6.4	.13
80.5	99.1	55.0	95.8	3.3	.4	7.2	6.8	.06
83.0	99.3	57.5	96.3	3.0	.3	7.2	6.9	.04
85.5	99.5	60.0	96.7	2.8	.2	7.2	7.0	.03

Data for Plotting Dilution Factor Curve for Produced-Volume Ratios of 80 Percent of Maximum

% Volume injection	Maximum R	80% of maximum R	C_i/C_o
1.25	0.63	0.05	21.00
2.50	.13	.10	11.00
5.00	.25	.20	6.00
10.00	.50	.40	3.50
20.00	1.20	.96	2.04
30.00	1.85	1.48	1.68
40.00	2.30	1.84	1.54
70.90	3.00	2.40	1.42

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