Oil Recovery by Gravity Drainage Into Horizontal Wells Compared With Recovery From Vertical Wells

Herman Dykstra, SPE, Consultant, and **Wade Dickinson,** SPE, Petrolphysics Inc.

Summary. Gravity drainage is a significant factor in many EOR projects, particularly those involving steam stimulation and extended recovery from depleted reservoirs. This paper compares the effect of dip, reservoir thickness, oil mobility, and well spacing on production from horizontal vs. vertical wells. Total production from vertical and horizontal wells as a function of time also is compared. The basic physical concept involved in this study is the constriction coefficient. For a horizontal well, the constriction coefficient is larger than that for a vertical well at the start of drainage but that difference decreases with time.

Introduction

The drilling of horizontal, or radial, wells has expanded rapidly during the last few years.[1] The advantage of horizontal wells vs. vertical wells is that horizontal wells can be drilled parallel to bedding planes and along a formation strike, thus opening up more of the formation to the wellbore.

Joshi[2] provided an extensive list of references on horizontal well technology and presented equations of steady-state flow for multiple radials at one or more elevations. Joshi[3] also summarized the development of Borisov's[4] equations for steady-state flow into horizontal, or radial, wells and presented the results of calculated horizontal/vertical-well PI ratio for a constant-pressure outer boundary. The ratios were determined as functions of well spacing, formation thickness, and length of the horizontal well, for vertical/horizontal permeability ratios of 0.1, 0.5, and 1.0.

Butler and Stephens[5] and Joshi and Threlkeld[6] described the application of horizontal wells in thermally stimulated heavy-oil reservoirs. Both works present the results of calculations and experiments on gravity-drainage oil recovery into horizontal wells stimulated by steam injection.

We present calculations of gravity-drainage oil recovery from vertical and horizontal wells and compare these recoveries to determine the ratio of horizontal/vertical-well flow rates and recoveries. Four cases were run. Two were for heavy-oil recovery from relatively flat beds that were thermally stimulated by steam injection to lower the oil viscosity, and two were for light-oil recovery from dipping formations to determine the advantage of horizontal wells in fields that may already be producing by gravity drainage.

Gravity Drainage From Flat Formations

In the calculation of heavy-oil recovery, Case 1 was for radial flow into a vertical well and Case 2 was for flow into a horizontal well at the base of the formation. **Fig. 1** shows the two cases schematically, with isometric views of one-quarter of the areas being drained. We assumed that the reservoir had low pressure and that a substantial portion of the volume around the vertical well, or above the horizontal well at the base of a bed, was heated by continuous steam injection. The heated oil, with its much lower viscosity, can then flow predominantly by gravity into the wellbore.[7]

Because our main interest is to determine the relative flow rates in horizontal and vertical wellbores, we simplify the process by assuming uniform mobility (permeability/viscosity ratio) throughout the formation. This may be a serious assumption, as far as rates are concerned, because not all the formation will be heated from a steam-stimulation job, nor is the ratio of vertical/horizontal permeability unity for all reservoirs. These two factors, however, affect vertical and horizontal wells in somewhat the same manner and so may have only a minor effect on the rate ratio. A simulation study is required to determine the actual effects.

For Case 1, we used Lefkovitz and Matthews'[8] method to calculate the gravity-drainage rate for radial flow into a vertical wellbore. The initial fluid head was assumed to equal the formation thickness. The calculations were made for flow from a cylinder with the same area as the well spacing of a square array of wells.

For Case 2, we used Cardwell and Parsons'[9] method, as described by Dykstra,[10] to calculate the gravity-drainage rate in a horizontal well at the base of a formation. The horizontal well is taken to be at the formation bottom in the center of a square being drained and is parallel to one of the sides. Its length is equal to the spacing between wells.

Because flow is constricted in the wellbore, it was necessary to calculate a constriction coefficient for flow into a slotted liner.[11] Dykstra[10] describes the constriction coefficient and how it is calculated. As these authors[10,11] indicate, the constriction to flow depends on the length of the flow path from the outer boundary to the slotted liner. For Case 2, we assumed that the length of the flow path was the distance between the gas/oil interface and the wellbore. Because this distance decreases with time as the interface drops toward the wellbore, it was necessary to calculate a changing constriction coefficient with time to calculate the gravity-drainage rate.

Data for Case 1 and 2 calculations were based on the Potter zone of the Midway Sunset field on the west side of the San Joaquin valley in California.[12] This zone has a gross interval of as much as 500 ft. Many parts of the zone have very good vertical permeability over intervals of almost 400 ft. The zone ranges in drilled depth from about 500 ft and has a low dip. The reservoir temperature varies with depth and ranges from 75 to 95°F. The oil has a narrow oil-gravity range and averages at 12°API. At 90°F, the reservoir oil viscosity is 11,000 cp, and at 200°F, it is 95 cp.

We used the following fluid and reservoir properties in the calculations: oil permeabilities of 100, 300, and 1,000 md; oil viscosity of 100 cp; porosity of 0.33; connate water saturation of 0.30; initial gas saturation of 0.05; initial oil saturation of 0.65; residual oil saturation of 0.15; vertical wellbore radius of 0.542 ft; and horizontal wellbore radius of 0.167 ft.

Calculations were made for spacings of 0.625, 1.25, 2.5, 5, 10, and 20 acres and formation thicknesses of 50, 100, 200, and 400 ft. For the vertical well, the fluid levels in the wellbore were based on formation thickness and ranged from 5 to 30 ft above the base of the formation.

Table 1 shows the effect of mobility on calculated flow rates and on the ratio of horizontal/vertical well rates for 2.5-acre spacing, with an initial fluid head of 200 ft, and for 5-acre spacing, with an initial fluid head of 100 ft. **Fig. 2** is a plot of the ratio vs. time. Results of the calculations indicate that mobility has only a small effect on the rate ratio at early times but has a slightly greater effect with time at higher mobilities.

Table 2 shows the effect of formation thickness, or initial fluid head, h, on calculated rates and ratios for 2.5-acre spacing and a mobility of 3 md/cp. **Fig. 3** is a plot of the ratio of horizontal/vertical well rates as a function of time. As can be seen, the initial fluid height (formation thickness) has a strong effect on the ratio, but time has only a minor effect. For h=300 and 400 ft, the ratio is below 1.0; i.e., a vertical well will produce at a greater rate than a horizontal well. For h=100 and 200 ft, the opposite is true.

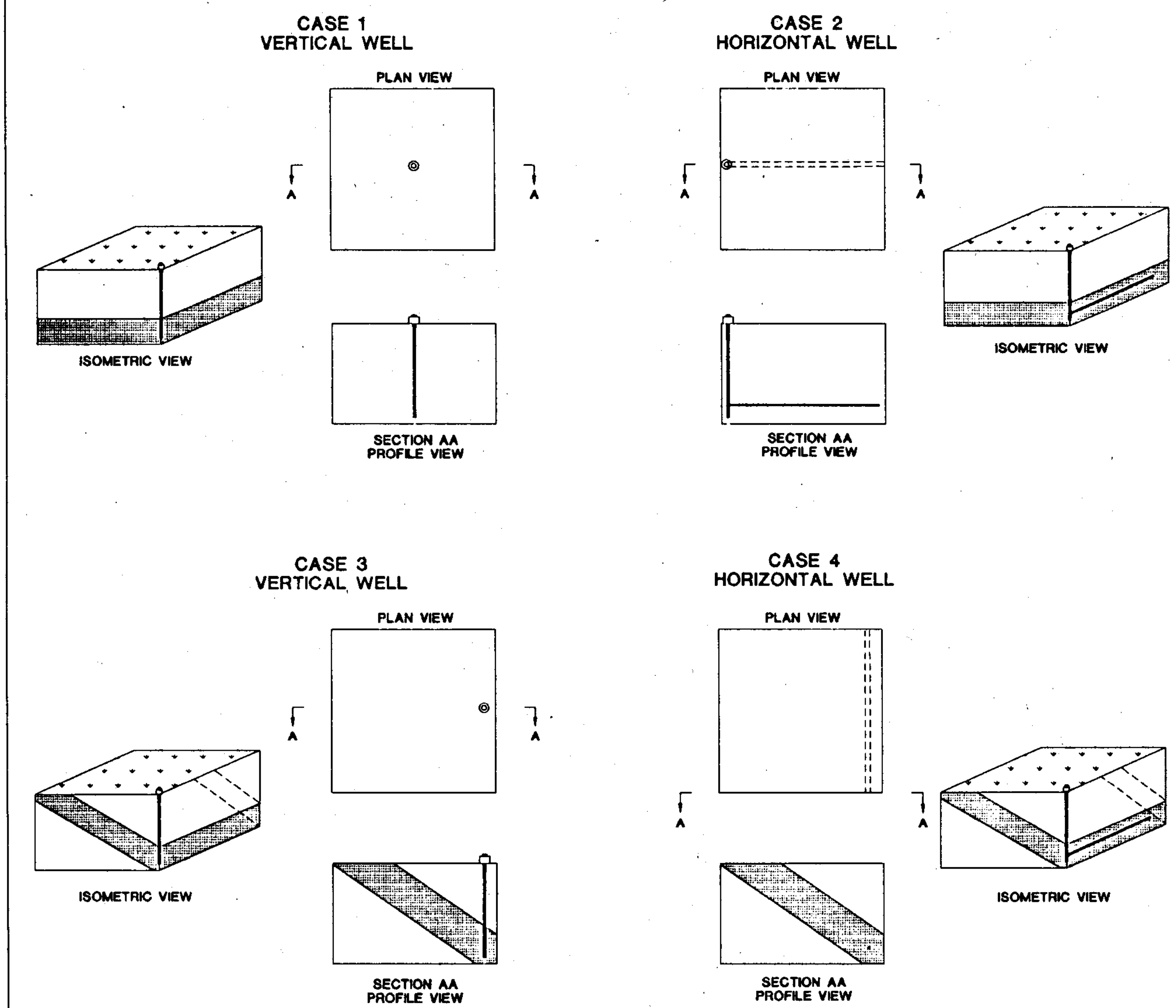

Fig. 1—Horizontal and vertical wells, Cases 1 through 4.

The same type of relation holds for other well spacings. Because time has only a small effect on the ratio of horizontal/vertical well rates, cumulative production at the end of 2 years can be compared. **Table 3** gives the calculated cumulative production and ratios, and **Fig. 4** shows the ratio as a function of h. Fig. 4 shows that when h is less than the well spacing (about 0.85 times distance between wells), a horizontal well will perform better than a vertical well, and when h is greater than the well spacing, a vertical well will perform better. These results can be used as criteria to decide whether a horizontal well is justified over a vertical well in a field where low-gravity oil is to be produced and a substantial portion of the formation is to be heated by steam stimulation. These results are also in line with Borisov,[4] who stated that when the length of the horizontal well is less than the formation thickness, the "drilling [of] horizontal wells becomes senseless."

Gravity Drainage From Dipping Formations

The situation is substantially different for drainage downdip in a vertical or a horizontal well from a formation at an angle to the horizontal. For these cases, oil moves parallel to the dip, with a flow area that is based on formation thickness and well spacing, in contrast to the previous cases where the flow area was based on well spacing only.

For economic gravity-drainage flow rates from a dipping formation, the mobility must be much higher than for the cases discussed above. To get sufficient mobility generally requires an oil with a high enough gravity to have sufficiently low oil viscosity at the prevailing reservoir temperature. For determination of required values of oil density and viscosity, an oil gravity of 40°API was chosen. We used the following fluid and reservoir properties in the calculation: oil permeabilities of 30, 60, and 120 md; oil viscosity of 1.98 cp; porosity of 0.25; connate water saturation of 0.25; initial gas saturation of 0.05; initial oil saturation of 0.70; residual oil saturation of 0.125; wellbore radius of 0.25 ft; and dip angle of 30°.

Case 3 results are for a vertical well, and Case 4 results are for a horizontal well drilled in the center of the formation at the same location as the vertical well, with a length equal to the well spacing. Fig. 1 shows the two cases schematically. As with Case 2 above, Dykstra's[10] method was used to calculate the gravity-drainage flow rate.

Table 4 shows the effect of formation thickness on flow rates and on ratio of horizontal/vertical well rates over 15 years of production for 40-acre spacing and a mobility of 20 md/cp. As expected, the calculations show that the flow rate is directly proportional to the formation thickness. **Fig. 5** is a plot of the ratio of horizontal/vertical well rates for h=20 and 100 ft. Fig. 5 indicates that formation thickness has only a small effect on the rate ratio. The ratio starts at about 2.5 and increases slowly the first 4 years, then decreases to less than 1.0 after 12.5 years of production.

TABLE 1—EFFECT OF MOBILITY ON GRAVITY-DRAINAGE RATE VS. TIME

Time (years)	q_V (BOPD)	q_H (BOPD)	q_H/q_V	q_V (BOPD)	q_H (BOPD)	q_H/q_V	q_V (BOPD)	q_H (BOPD)	q_H/q_V
	$M=1$ md/cp			$M=3$ md/cp			$M=10$ md/cp		
2.5-Acre Spacing and 200-ft Initial Fluid Head									
0.5	10.38	15.52	1.5	31.0	46.5	1.5	99.6	149.0	1.5
110.32	15.37	1.49	30.5	45.5	1.49	93.2	140.0	1.49	
210.19	15.16	1.49	29.4	43.8	1.49	83.7	123.7	1.48	
310.07	14.97	1.49	28.4	42.3	1.49	75.1	108.9	1.45	
49.94	14.79	1.49	27.4	40.8	1.49	67.8	95.5	1.41	
59.82	14.62	1.49	26.4	39.3	1.49	61.4	83.6	1.36	
5-Acre Spacing and 100-ft Initial Fluid Head									
0.5	2.36	11.94	5.06	7.2	36.1	5.01	24.0	117.9	4.91
12.36	11.84	5.02	7.17	35.5	4.95	23.7	112.4	4.75	
22.35	11.72	4.99	7.11	34.5	4.85	23.0	102.8	4.47	
32.34	11.61	4.96	7.05	33.6	4.77	22.4	94.1	4.20	
42.34	11.50	4.91	6.99	32.8	4.69	21.8	86.1	3.96	
52.33	11.40	4.89	6.93	31.9	4.60	21.2	78.8	3.72	

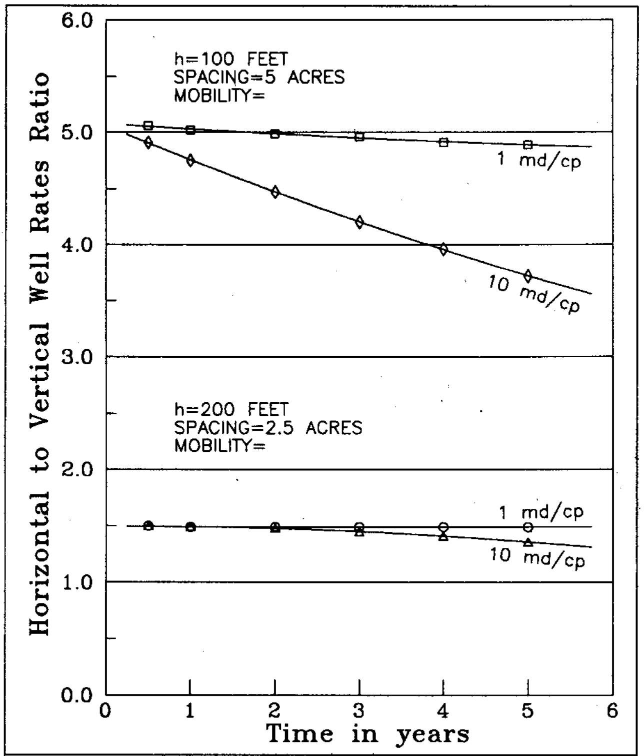

Fig. 2—Effect of mobility on ratio of horizontal/vertical-well rates, Cases 1 and 2.

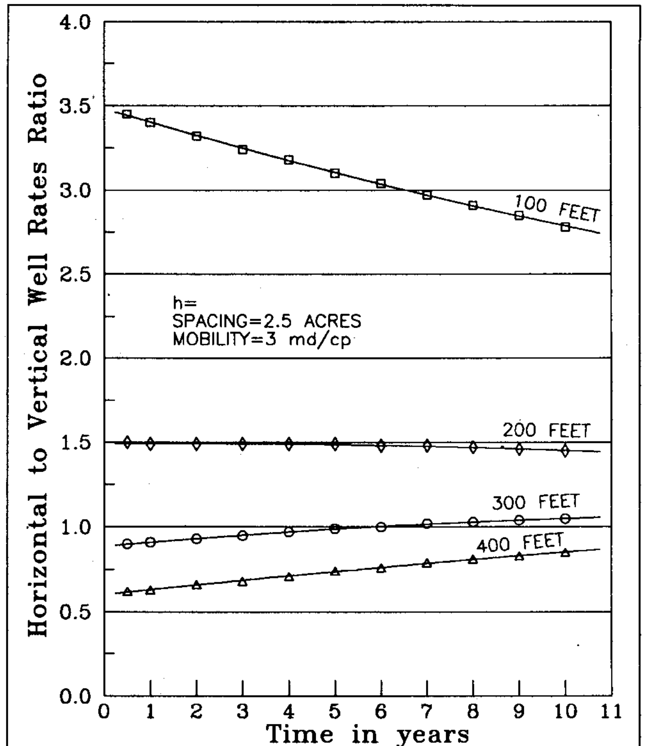

Fig. 3—Effect of formation thickness on ratio of horizontal/vertical-well gravity-drainage rates, Cases 1 and 2.

TABLE 2—EFFECT OF INITIAL FLUID HEAD ON GRAVITY-DRAINAGE RATE VS. TIME

2.5-Acre Spacing and Mobility of 3 md/cp

Time (years)	q_V (BOPD)	q_H (BOPD)	q_H/q_V	q_V (BOPD)	q_H (BOPD)	q_H/q_V	q_V (BOPD)	q_H (BOPD)	q_H/q_V	q_V (BOPD)	q_H (BOPD)	q_H/q_V
	$h=400$ ft			$h=300$ ft			$h=200$ ft			$h=100$ ft		
0.5	123.1	75.9	0.62	69.7	62.9	0.90	31.0	46.5	1.50	7.48	25.8	3.45
1	118.7	74.6	0.63	67.8	61.7	0.91	30.5	45.5	1.49	7.41	25.2	3.40
2	110.6	72.6	0.66	64.2	59.8	0.93	29.4	43.8	1.49	7.28	24.2	3.32
3	103.2	70.7	0.68	60.9	57.9	0.95	28.4	42.3	1.49	7.15	23.2	3.24
4	96.6	68.8	0.71	57.9	56.1	0.97	27.4	40.8	1.49	7.02	22.3	3.18
5	90.6	66.9	0.74	55.1	54.4	0.99	26.4	39.3	1.49	6.90	21.4	3.10
6	85.1	65.1	0.76	52.4	52.6	1.00	25.6	37.9	1.48	6.77	20.6	3.04
7	80.1	63.2	0.79	50.0	50.9	1.02	24.7	36.5	1.48	6.66	19.8	2.97
8	75.6	61.3	0.81	47.7	49.2	1.03	23.9	35.1	1.47	6.54	19.0	2.91
9	71.4	59.5	0.83	45.6	47.5	1.04	23.2	33.8	1.46	6.43	18.3	2.85
10	67.5	57.6	0.85	43.6	45.9	1.05	22.4	32.5	1.45	6.32	17.6	2.78

TABLE 3—EFFECT OF SPACING AND INITIAL FLUID HEAD ON HORIZONTAL/VERTICAL-WELL RATIO CUMULATIVE GRAVITY-DRAINAGE RECOVERY

Spacing			Cumulative Recovery at End of 2 Years for $M=3$ md/cp (bbl×10^3)		
Acres	Feet	h (ft)	q_V (BOPD)	q_H (BOPD)	q_H/q_V
0.625	165	400	79.6	20.1	0.25
1.25	233	400	85.9	34.0	0.40
		300	49.9	29.1	0.58
		200	22.85	22.38	0.98
2.5	330	400	86.8	54.9	0.63
		300	49.5	45.4	0.92
		200	22.25	33.53	1.51
		100	5.41	18.55	3.43
5.0	467	400	112.0	112.0	1.00
		300	47.9	67.9	1.42
		200	21.3	48.6	2.28
		100	5.23	26.21	5.01
10	660	200	20.3	68.9	3.40
		100	4.96	36.8	7.4
		50	1.23	19.80	16.1
20	933	50	1.16	27.96	24.0

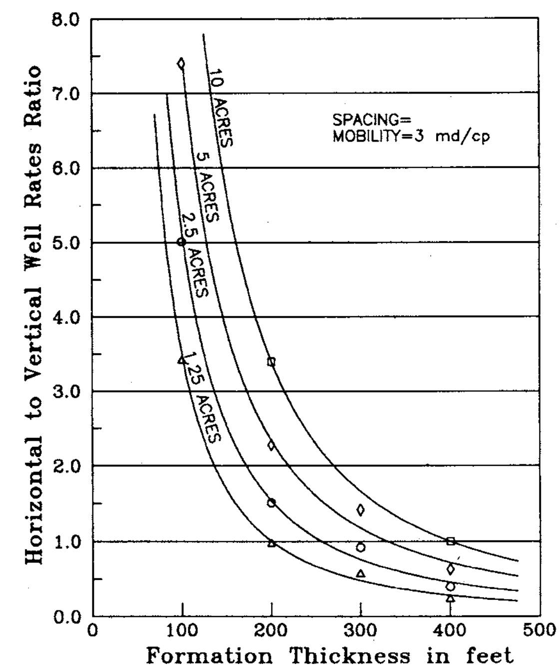

Fig. 4—Ratio of horizontal/vertical-well cumulative gravity-drainage recoveries at end of 2 years, Cases 1 and 2.

Table 5 shows the effect of mobility on flow rates and ratios for 40-acre spacing and formation thickness of 40 ft for mobilities of 10 and 40 md/cp. **Fig. 6** shows a plot of the rate ratios. For each mobility, the ratio starts at a value slightly less than 2.5 and then gradually increases to just more than 2.6 before decreasing. The time at which the ratio begins to decline is inversely proportional to mobility, occurring at about 2.5, 5, and 10 years for mobilities of 40, 20, and 10 md/cp, respectively.

This behavior occurs because the constriction coefficient for the horizontal well is larger than that for a vertical well at the start of drainage, but it decreases more rapidly for the horizontal well because the interface decreases more rapidly toward the producing well level than it does for the vertical well. The greater the mobility, the more quickly the effect of the changing constriction coefficient is felt.

Table 6 shows the effect of 80-, 20-, and 10-acre spacing with a formation thickness of 40 ft and a mobility of 20 md/cp. **Fig. 7** shows the ratio of horizontal/vertical well rates. For each spacing, the ratio first increases slowly and then decreases after a period of time that is proportional to the spacing. The closer the well spacing, the more quickly the ratio begins to decrease.

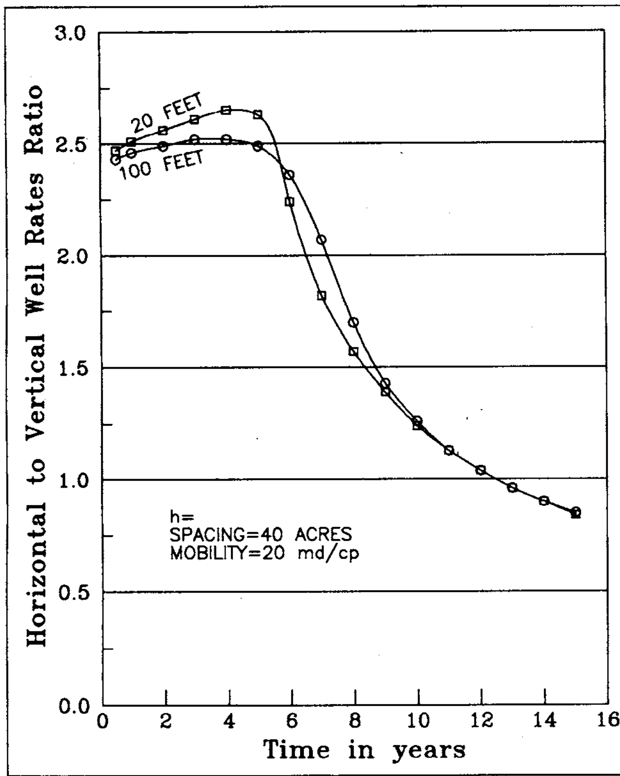

Fig. 5—Effect of formation thickness on ratio of horizontal/vertical-well gravity-drainage rates, Cases 3 and 4.

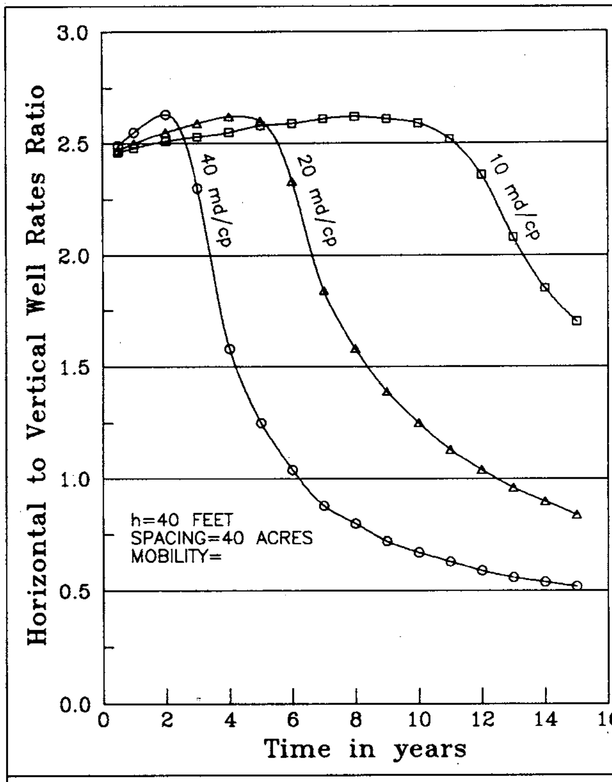

Fig. 6—Effect of mobility on ratio of horizontal/vertical-well gravity-drainage rates, Cases 3 and 4.

TABLE 4—EFFECT OF FORMATION THICKNESS ON DOWNDIP GRAVITY-DRAINAGE FLOW RATE VS. TIME

40-Acre Spacing and Mobility of 20 md/cp									
	$h=100$ ft			$h=40$ ft			$h=20$ ft		
Time (years)	q_V (BOPD)	q_H (BOPD)	q_H/q_V	q_V (BOPD)	q_H (BOPD)	q_H/q_V	q_V (BOPD)	q_H (BOPD)	q_H/q_V
0.5	202.4	491.3	2.43	81.0	199.7	2.47	40.5	100.1	2.47
1	199.5	489.9	2.46	79.8	199.5	2.50	39.9	100.1	2.51
2	194.9	486.2	2.49	77.9	198.9	2.55	39.0	99.9	2.56
3	190.7	480.4	2.52	76.3	197.9	2.59	38.1	99.5	2.61
4	186.6	471.0	2.52	74.7	195.8	2.62	37.3	98.7	2.65
5	182.6	454.1	2.49	73.1	190.0	2.60	36.5	96.1	2.63
6	178.7	421.2	2.36	71.5	166.6	2.33	35.7	80.1	2.24
7	174.8	362.0	2.07	69.9	128.3	1.84	35.0	63.7	1.82
8	170.9	290.9	1.70	68.4	107.8	1.58	34.2	53.8	1.57
9	167.1	239.0	1.43	66.8	92.9	1.39	33.4	46.5	1.39
10	163.3	205.3	1.26	65.3	81.4	1.25	32.7	40.7	1.24
11	159.6	181.1	1.13	63.8	72.3	1.13	31.9	36.1	1.13
12	155.8	162.2	1.04	62.3	64.8	1.04	31.2	32.4	1.04
13	152.2	146.7	0.96	60.9	58.6	0.96	30.4	29.3	0.96
14	148.6	133.7	0.90	59.4	53.4	0.90	29.7	26.7	0.90
15	145.0	122.6	0.85	58.0	49.0	0.84	29.0	24.5	0.84
Percent*	17.5	32.5	1.86	17.5	32.5	1.86	17.5	32.5	1.86

*Percent = cumulative production as percent of oil in place at start of drainage.

Tables 4 through 6 also list the cumulative recoveries and ratios at the end of 15 years as a percent of the oil in place at the start of drainage. Table 4 shows that the ratio of horizontal/vertical recoveries is independent of the formation thickness. The ratio is 1.86. Tables 4 and 5 indicate that the ratio decreases as mobility increases from 2.43 at 10 md/cp to 1.25 at 40 md/cp. Tables 4 and 6 indicate that the ratio increases as spacing increases from 1.20 at 10-acre spacing to 2.24 at 80-acre spacing. At infinite time, the cumulative recoveries for Cases 3 and 4 will be the same.

Conclusions

1. For flat formations (Cases 1 and 2), time has little to almost no effect on the ratio of horizontal/vertical well rates.

2. For flat formations at thicknesses less than 0.85 times the distance between wells, a horizontal well will produce better than a vertical well, whereas at formation thicknesses greater than this, a vertical well will produce better.

3. For dipping formations (Cases 3 and 4) with gravity-drainage oil flow in homogeneous formations, where thickness is small relative to well spacing, a horizontal well initially will produce at about 2.5 times the rate of a vertical well.

4. For flat formations, formation thickness affects the ratio of horizontal/vertical-well flow rate. But for dipping formations, formation thickness has essentially no effect on the ratio of horizontal/vertical-well flow rate.

5. The time at which the ratio of horizontal/vertical-well rates begins to decrease is inversely proportional to mobility but is directly proportional to well spacing.

6. For flat formations, mobility has little effect on the ratio of horizontal/vertical-well flow as a function of time. For dipping for-

TABLE 5—EFFECT OF MOBILITY ON DOWNDIP GRAVITY-DRAINAGE FLOW RATE VS. TIME

40-Acre Spacing Formation Thickness of 40 ft						
	$M=10$ md/cp			$M=40$ md/cp		
Time (years)	q_V (BOPD)	q_H (BOPD)	q_H/q_V	q_V (BOPD)	q_H (BOPD)	q_H/q_V
0.5	40.6	99.7	2.46	160.6	399.8	2.49
1	40.2	99.6	2.48	156.6	398.8	2.55
2	39.7	99.5	2.51	149.7	393.4	2.63
3	39.2	99.3	2.53	143.3	530.5	2.30
4	38.8	99.1	2.55	137.0	215.8	1.58
5	38.4	98.9	2.58	130.9	163.1	1.25
6	38.0	98.5	2.59	124.9	129.8	1.04
7	37.6	98.0	2.61	119.0	107.0	0.88
8	37.2	97.3	2.62	113.3	90.6	0.80
9	36.8	96.2	2.61	107.8	78.1	0.72
10	36.4	94.3	2.59	102.4	68.5	0.67
11	36.0	90.7	2.52	97.2	60.8	0.63
12	35.6	83.9	2.36	92.2	54.5	0.59
13	35.3	73.6	2.08	87.5	49.3	0.56
14	34.9	64.7	1.85	82.9	45.0	0.54
15	34.5	58.6	1.70	78.5	41.2	0.52
Percent*	9.5	23.1	2.43	29.7	40.4	1.36

*Percent = cumulative production as percent of oil in place at start of drainage.

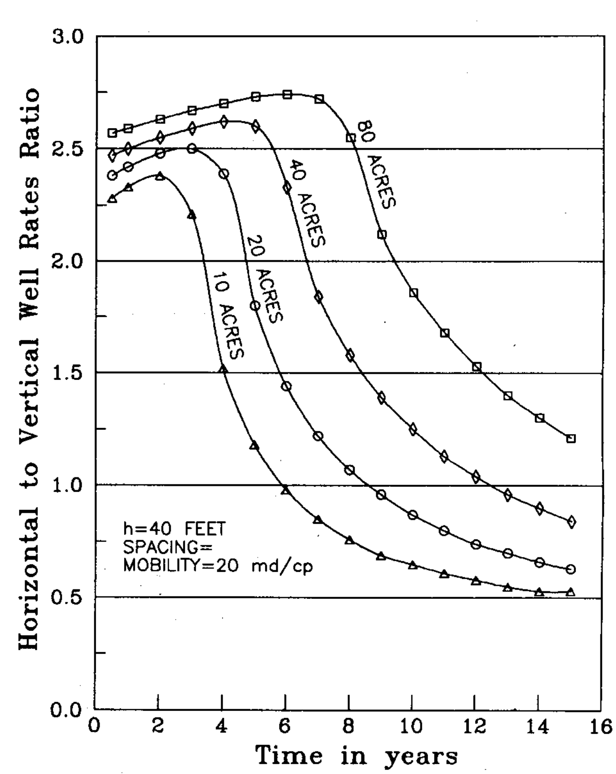

Fig. 7—Effect of well spacing on ratio of horizontal/vertical-well gravity-drainage rates, Cases 3 and 4.

Authors

Dykstra

Dickinson

Herman Dykstra is a consultant in Concord, CA. Previously, he worked at Standard Oil Co. of California in La Habra (1963–71, 1946–47, and 1943–44) and San Francisco (1961–63), Chevron Research Corp. in La Habra (1947–61), and the U.S. Army (1944–46). His research interests include fluid flow through porous media, various EOR processes, reservoir engineering, material balance and water-influx calculations, thermal methods, pressure-buildup analysis, gravity-drainage calculations, and computer applications. He holds BS and MS degrees from the U. of Michigan, both in chemical engineering. A Distinguished Member and recipient of the 1971 Lester C. Uren Award, Dykstra served on Technical Program committees for the 1972, 1973, and 1974 Annual Meetings. He was Membership Chairman for the Los Angeles Basin section during 1966–69 and served on the Symbols and Metrication Committee during 1965–70. Wade Dickinson is president of Petrolphysics Inc. in San Francisco and a visiting lecturer at the U. of California, Berkeley. Previously, he worked at the Bechtel Group Inc., Rand Corp., the U.S. Congress, and the U.S. Air Force in fields of nuclear power, satellite reconnaissance, and nuclear weapons. He has developed products for the growth stimulation of cattle and hogs and for ultrasonic cardiology, ultrasonic nondestructive testing, seed testing and planting, integrated circuit instrumentation, and robotics. Dickinson holds a BS degree in military engineering from the U.S. Military Academy and is a graduate of the Oak Ridge School of Reactor Technology.

mations, mobility has a substantial effect on that ratio as a function of time.

Nomenclature

h = formation thickness, ft
M = mobility, md/cp
q_H = horizontal well rate (Case 2), BOPD
q_V = radial flow rate into vertical well (Case 1), BOPD
q_H/q_V = ratio of horizontal/vertical-well flow rate

References

1. Moritis, G.: "Worldwide Horizontal Drilling Surges," *Oil & Gas J.* (1989) **87**, 53-63.
2. Joshi, S.D.: "A Review of Horizontal Well and Drainhole Technology," paper SPE 16868 presented at the 1987 SPE Annual Technical Conference and Exhibition, Dallas, Sept. 27-30.
3. Joshi, S.D.: "Augmentation of Well Productivity With Slant and Horizontal Wells," *JPT* (June 1988) 729-39; *Trans.*, AIME, **285**.
4. Borisov, Ju P.: *Oil Production Using Horizontal and Multiple Deviation Wells*, Nedra, Moscow (1964); R&D Library translation by J. Strauss, S.D. Joshi (ed.), Phillips Petroleum Co., Bartlesville, OK (1984).
5. Butler, R.M. and Stephens, J.D.: "The Gravity Drainage of Steam Heated Oil to Parallel Horizontal Wells," *J. Cdn. Pet. Tech.* (1981) **21**, 90-96.
6. Joshi, S.D. and Threlkeld, C.B.: "Laboratory Studies of Thermally Aided Gravity Drainage Mechanism Using Horizontal Wells," paper presented at the 1984 Annual Advances in Petroleum Recovery and Upgrading Technology Conference, Calgary, June 14-15.
7. Burns, J.: "A Review of Steam Soak Operation in California," paper SPE 1731 presented at the 1967 SPE Annual Meeting, Los Angeles, Feb. 19-23.
8. Matthews, C.S. and Lefkovitz, H.D.: "Gravity Drainage Performance of Depletion Type Reservoir in the Stripper Stage," *Trans.*, AIME (1956) **207**, 265-74.
9. Cardwell, W.T. and Parsons, R.L.: "Gravity Drainage Theory," *Trans.*, AIME (1949) **179**, 199-215.
10. Dykstra, H.: "The Prediction of Oil Recovery by Gravity Drainage," *JPT* (May 1978) 818-30; *Trans.*, AIME, **265**.
11. Dodson, C.R. and Cardwell, W.T.: "Flow Into Slotted Liners and an Application to the Theory of Core Analysis," *Trans.*, AIME (1945) **160**, 56-64.
12. Land, P.E. and Anderson, D.N.: "Midway Sunset Oil Field," California State Div. of Oil & Gas, Summary of Operations—California Oil Fields, Sacramento (1965) **51**, No. 2, 21-29.

SI Metric Conversion Factors

acre	× 4.046 873	E−01	=	ha
°API	141.5/(131.5+°API)		=	g/cm³
bbl	× 1.589 873	E−01	=	m³
cp	× 1.0*	E−03	=	Pa·s
ft	× 3.048*	E−01	=	m
°F	(°F−32)/1.8		=	°C
md	× 9.869 233	E−04	=	μm²

*Conversion factor is exact.

SPEFE

Original SPE manuscript received for review Oct. 9, 1989. Revised manuscript received Sept. 4, 1991. Paper accepted for publication Dec. 13, 1991. Paper (SPE 19827) first presented at the 1989 SPE Annual Technical Conference and Exhibition held in San Antonio, Oct. 8-11.

TABLE 6—EFFECT OF SPACING ON DOWNDIP GRAVITY-DRAINAGE FLOW RATE VS. TIME

Formation Thickness of 40 ft and Mobility of 20 md/cp									
	80-Acre Spacing			20-Acre Spacing			10-Acre Spacing		
Time (years)	q_V (BOPD)	q_H (BOPD)	q_H/q_V	q_V (BOPD)	q_H (BOPD)	q_H/q_V	q_V (BOPD)	q_H (BOPD)	q_H/q_V
0.5	110.3	283.4	2.57	59.1	140.5	2.38	43.1	98.4	2.28
1	109.1	283.2	2.59	58.0	140.1	2.42	42.0	97.8	2.33
2	107.5	282.9	2.63	56.1	139.0	2.48	40.0	95.2	2.38
3	105.9	282.4	2.67	54.4	136.1	2.50	38.2	84.4	2.21
4	104.4	281.7	2.70	52.7	125.7	2.39	36.4	55.4	1.52
5	102.9	280.6	2.73	51.0	92.0	1.80	34.6	40.7	1.18
6	101.4	278.3	2.74	49.3	70.8	1.44	32.9	32.4	0.98
7	100.0	272.5	2.72	47.7	58.3	1.22	31.2	26.7	0.85
8	98.5	251.3	2.55	46.1	49.3	1.07	29.5	22.5	0.76
9	97.0	205.3	2.12	44.5	42.5	0.96	28.0	19.4	0.69
10	95.6	177.9	1.86	42.9	37.3	0.87	26.4	17.1	0.65
11	94.2	157.8	1.68	41.4	33.1	0.80	24.9	15.1	0.61
12	92.7	141.5	1.53	39.9	29.7	0.74	23.5	13.6	0.58
13	91.3	128.0	1.40	38.4	26.8	0.70	22.2	12.3	0.55
14	89.9	116.7	1.30	37.0	24.5	0.66	20.9	11.2	0.53
15	88.5	107.0	1.21	35.6	22.4	0.63	19.6	10.3	0.53
Percent*	12.5	28.0	2.24	23.8	36.5	1.53	31.1	40.2	1.29

*Percent = cumulative production as percent of oil in place at start of drainage.