Realistic K Values of C_7+ Hydrocarbons for Calculating Oil Vaporization During Gas Cycling at High Pressures

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Introduction

Although water will displace oil from a petroleum reservoir to a greater extent than gas will, there are some reservoirs in which gas rather than water should be used for pressure maintenance. This is indicated by the high-percentage oil recovery in the case history reports on the Pickton field[1] in East Texas and the Raleigh field[2] in Mississippi. In gas cycling, total oil recovery includes vaporized products from the immobile oil in addition to oil produced by displacement. If a large part of the immobile oil is vaporized, total oil recovery may be higher than that obtainable from pressure maintenance by water injection. However, the amount of immobile oil vaporized may range from almost 0 to 100 percent, and no simple and reliable method has been presented in the literature for calculating oil vaporization. Development of such a method was the purpose of this study.

Several papers concerning the calculation of oil vaporization have been published,[3-6] and each is based on the concept dealing with K values — equilibrium constants for the various components in reservoir oils. (K for a component in a system of vapor and liquid in equilibrium is the mole fraction in the vapor phase divided by the mole fraction in the liquid phase.) This appears to be the most logical approach. Yet, the problem is too great for a perfect solution, even with modern laboratories to analyze oils and high-speed digital computers to perform calculations; the number of components in reservoir oils is too

large. Because of their complexity no two reservoir oils are exactly alike. Also, K values change not only with variations in pressure and temperature but also with composition of the reservoir oil. In addition, during gas cycling, the lighter hydrocarbons tend to vaporize first. Thus, the reservoir oil becomes more dense and less volatile as gas cycling continues. Furthermore, the greatest amount of oil vaporization occurs near the injection well. Therefore, a simplified method is required for calculating oil vaporization because a rigorous method is not practical.

The present methods of calculating vaporization generally require knowledge of the reservoir oil composition in which the mole fractions of the lighter components through hexanes are given; the remaining oil is described as C_7+ (heptanes and others of greater molecular weights). Assigning one K value for the C_7+ system provides the simplest solution, but this incorrectly assumes that K for C_7+ does not change as gas cycling continues. This assumption can cause large errors because the K value may become less than a thousandth of the original after a large amount of oil vaporization. Another way to solve the problem is to determine changing K values for C_7+ according to how much of the C_7+ has been vaporized. To determine these values a sample of the reservoir oil is injected into a pressure-volume cell, and dry gas is batched in and out of the cell. Appropriate measurements and tests are made to determine K

Given this simple method for calculating vaporization, along with laboratory data that indicate which conditions of pressure, temperature, and type of oil are favorable for maximum vaporization, we can greatly enhance the prospects for successful gas cycling.

values of C_7+ for various amounts of C_7+ vaporized. This solution is time consuming and valid for only one specific reservoir oil, and the batching of gas in and out of a PV cell differs somewhat, with respect to vaporization, from the flow of gas through a reservoir. Nonetheless, this is a useful approach to the problem.

The empirical method described in this paper also has imperfections; however, it provides a simple procedure. The resulting errors are within acceptable limits for calculating total oil recovery by gas cycling when considering the probable errors for other parts of the calculation such as (1) sweep efficiency, (2) relative permeability (k_g/k_o) values, and (3) volume of oil originally in place.

This method was developed with data from 13 experiments conducted by the Bureau of Mines, in which dry gas was cycled through a model oil reservoir.[7] These experiments covered various conditions of pressure (1,100, 2,600, and 4,100 psia), temperature (100, 175, and 250°F), and oil types (22°, 35°, and 45°API). Therefore, K values could be selected for the C_7+ part of the reservoir oil so that calculated vaporization was almost identical with that determined in the laboratory. To account for the differences in C_7+ for various oils, the C_7+ part was subdivided into 15 fractions according to distillation data of the stock-tank oil, and K values were established for each of these fractions. Even with this subdivision, the K values for the various fractions varied with types of oil, being greater for the more volatile oil. For simplicity, an empirical relationship was established using one set of curves that determined K values for the 15 fractions of C_7+. The product of K times the mole fraction of C_5+ in the initial reservoir oil ($K \times C_5+$) was in close agreement for the three types of oils used in the laboratory experiments. Thus, a set of curves was established showing $K \times C_5+$ values for each of the fractions at various pressures and temperatures. Also, an empirical equation is presented, providing a means for calculating $\log(K \times C_5+)$ values for any reservoir oil. By dividing the antilog of these values by the C_5+ mole fraction of the reservoir oil, each of the 15 K values can be obtained.

This paper is presented in two major sections. At the outset, because of its significance to reservoir engineers and others, the computer program for calculating oil vaporization is described. Following a discussion of the computer program is a description of the laboratory experiments performed in the study. For validity, calculated values of vaporization, based upon K values determined by the computer program, are compared with experimental values. Applications of findings to related problems are discussed in a separate section.

Computer Program for Calculating Oil Vaporization

A computer program was written* to express the process occurring when gas was cycled through the linear laboratory-model oil reservoir. For this idealized condition, the reservoir was considered to be divided into 20 PV cells. It was assumed that, at the start of an experiment, each cell contained known and identical amounts of reservoir oil. Then a selected amount (X volumes) of dry gas was injected into Cell 1, and equilibrium was assumed to occur. The resulting compositions and volumes of gas and oil were calculated by the flash procedure.[8] (Because some gas-saturated reservoir oil is vaporized, the gas volume increases and is called "enriched flashed gas". The concept is shown schematically in Fig. 1.)

All of the gas effluxed (enriched flashed gas) from Cell 1 was transferred to Cell 2, and another flash calculation was made. Again, some of the oil was vaporized, and through enrichment the gas volume increased. This same procedure of taking all of the gas from one cell and mixing it with liquids in the next cell was continued until gas (produced enriched gas) was voided from Cell 20. The vaporized products were determined by comparing the sum of the amounts of residual oils (liquids after multiples of X volumes of dry gas injected) in all 20 cells with that sum initially in the cells.

The injection of a known unit volume, X volumes, of gas into Cell 1 and the resultant passage of enriched gas through the remaining 19 PV cells is called a "loop". At the beginning of Loop 2 the oils of each of the 20 cells were the vapor-reduced liquids (liquids after X volumes) remaining after gas had passed through that cell in Loop 1. The volume of gas (X volumes) injected into Cell 1 was the same as for Loop 1 and represents the dry gas injected for cycling. The cell-by-cell flash analysis was repeated for Loop 2 through the 20 cells.

The amount of vaporized products for the loop was determined by comparing the amounts of residual oils for all cells with that for Loop 1. Generally, this procedure was continued for 120 loops, which provided cycled GOR's as great as those in the experiments. Thus, for any specific loop (1) the percent of each component vaporized, (2) the liquid volume of
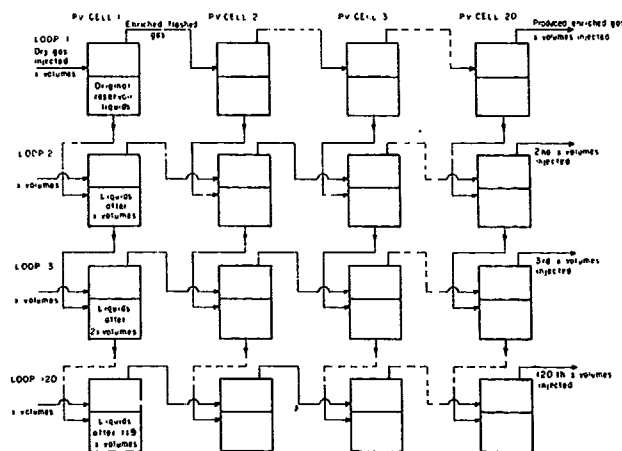

Fig. 1—Schematic of cycling concept.

reservoir oil, and (3) the relative liquid volume of C_5+ reservoir oil can be determined for the system of 20 cells or for the 20 cells individually.

To design a computer program so that the mathematical model would simulate laboratory conditions more closely than the one used, the concept of simultaneously displacing gas from one cell to the next could have been used. However, this concept would have complicated the program, and many computers do not possess sufficient memory capacity to handle such a large program. The computer program used here furnished correct answers with only simple manipulations. For example, assume that it is desirable to know the liquid volume in each cell after 40 injections, or loops, of gas have passed through Cell 20. To simulate simultaneous displacement of gas from one cell to the next by this procedure, Cell 19 would be represented by the data from an additional injection of gas in Loop 41, Cell 18 by Loop 42, and so on with Cell 1 by Loop 59. Then, by reference to printouts by cells for Loops 40 through 59, the liquid volumes in each cell could be determined when 40 injected gas volumes had passed through Cell 20.

Basic input data on each hydrocarbon fraction for the computer program include (1) mole fraction of reservoir oil, (2) mole fraction of gas used in cycling, (3) equilibrium constant, (4) molecular weight, and (5) specific gravity. The molecular weights and specific gravities are required to convert the mole fractions of oil into liquid volumes.

Number of Cells and Ratio of Moles of Gas to Moles of Oil

A system of 20 cells with 0.2 mole of initial reservoir oil in each and with 0.8 mole of gas injection for each loop was chosen after making several calculations in which the systems for various numbers of cells and oil saturations were varied. The number of cells selected for examination were 1, 5, 10, 20, and 50. The selected ratios of moles of gas injected per loop to moles of oil in each cell were 1:1, 4:1, and 20:1, which correspond to oil-saturation percentages of 51, 21, and 5, respectively. Calculated values for various combinations of these variables are shown in Table 1. (These calculated values are for the 35°API oil at 2,600 psia and 175°F.)

The table shows that the dominant variable is the amount of gas cycled for the total oil in the number of cells used. For systems containing 10 or more cells, the calculated oil vaporizations are in close agree-

ment. For added assurance, a system of 20 cells was selected. Varying the ratio of moles of gas injected to moles of oil in each cell scarcely influenced calculated oil vaporization.

Method of Selecting K Values
Division of Reservoir Oil into 23 Fractions

Reservoir oil was arbitrarily divided into 23 fractions for this study. The lighter components of methane through hexanes were divided into Fractions 1 through 8. Heptanes and hydrocarbons with higher molecular weights were subdivided into Fractions 9 through 23. These heavier hydrocarbons were subdivided so that changes in the rate of vaporization as gas cycling continued could be described better.

The heptanes-plus oil was subdivided by referring to crude oil distillation data[9] obtained by the Bureau of Mines Routine Method.* Based upon a study of several crude oil analyses, both by the Bureau of Mines Routine Method and by the GLC (gas-liquid chromatographic) method, it was found that the volume distilled off through the second fraction was approximately the same as the hexanes and lighter components found from the GLC analyses. Furthermore, the cut-point temperature between hexanes and heptanes for fractional analysis distillations at atmospheric pressure is approximately that for the end of distillation Fraction 2. Therefore, the C_7+ reservoir oil was divided into 15 components with distillation Fraction 3 representing the first component or reservoir-oil Fraction 9. (The first eight reservoir-oil fractions represent the components of methane through hexanes.) Distillation Fractions 4 through 15 represent the next 12 components. Components 14 and 15 constitute the residuum — Component 14 is 90 percent, and Component 15 is the remaining 10 percent. Distillation fraction numbers equivalent to various reservoir-oil fraction numbers are shown in Columns 1 and 2 of Table 2.

The preceding method of classifying C_7+ oil by oil distillation fractions is subject to some pitfalls and criticism. The composition of samples of stock-tank oil may vary with (1) the number of separators used, (2) both separator pressures and temperatures, (3) atmospheric pressure, and (4) the amount of free gas being produced with the oil. Composition changes, owing to changes in the first three variables, primarily affect the amount of hexanes and lighter components in the oil. Thus, their general effect on the C_7+ oil is minimal; however, the effect of high GOR's on the C_7+ oil can be significant, especially when the field reservoir is deep. Under no normal conditions should stock-tank oil be considered representative of the condensate formed in a high-pressure gas reservoir.

The C_7+ part of stock-tank oils, having identical gravities, may vary greatly; for example, Fraction 7 may be 70 percent aromatic and 30 percent paraffinic

TABLE 1—VAPORIZATION FOR VARIOUS COMBINATIONS OF OIL SATURATION, CELLS, AND LOOPS

Oil saturation, percent	No. of cells in system	Gas cycled, Mcf/bbl of immobile stock-tank oil							
		4.56		9.13		18.26		27.38	
		Loops	Vap., percent	Loops	Vap., percent	Loops	Vap., percent	Loops	Vap., percent
51	10	40	11.23	80	20.48	160	*29.7	240	*33.9
21	20	20	11.27	40	20.68	80	29.94	120	34.09
5	50	10	11.24	20	20.71	40	30.01	60	34.15
21	1	1	8.86	2	*15.9	:	*24.7	6	*29.5
do.	5	5	10.90	10	19.71	20	29.01	30	33.2
do.	10	10	11.21	20	20.28	40	29.63	60	33.86
do.	20	20	11.27	40	20.68	80	29.94	120	34.09

* Interpolated from plotted data.

in one crude oil and 30 percent aromatic and 70 percent paraffinic in another. In this study, only the boiling-point temperature was assumed to affect the K values; the ratio of paraffins to aromatics may also affect the values. But accounting for this variable would be too complex and time consuming for inclusion in this paper.

Flash calculations require that the reservoir oil composition be expressed as mole fraction or mole percent. The routine distillation data are given as liquid percent. Therefore, to convert to mole percent, the liquid percent of each component is multiplied by its specific gravity and divided by the molecular weight. These values are normalized so that the distillation fractions, representing C_7+ oil, equal 100 mole percent. Both the specific gravity and the average molecular weight for the components of a 35°API crude oil distillation (Table 2) vary some with different types of oil (not shown). Molecular weights (Table 2) were determined by the procedure reported by Eilerts et al.[10] (Small errors in molecular weights are not significant because they are cancelled in converting liquid volumes to mole volumes and back to liquid volumes.) Vaporization is expressed in terms of stock-tank oil so the specific gravities are given at 60°F and atmospheric pressure. For calculations concerned with two-phase flow, it may be necessary to correct specific gravities to reservoir conditions.

Analysis of reservoir oils usually includes inerts, hydrocarbons of methane through the hexanes, and the remainder, which is C_7+ (heptanes and heavier). In this study only a trace of inerts was present in

either the oils or the gas used for cycling. Molar compositions of oils for each of the 13 experiments were divided into 23 fractions and are shown in Tables 3 and 4.

K Values for C_7+ Reservoir Oil

K values for Fractions 9 through 22 were determined by trial and error for each of the 13 experiments. An exceptionally small K value, 1×10^{-7}, was chosen for Fraction 23 to provide at least a trace of liquid in Cell 1 at all times as required for the computer program. As K values decrease with an increase in the boiling-point temperature of components, semilog plots were used to extrapolate K values given in the NGPSA (Natural Gas Processors Suppliers Association) Data Book[11] to correspond to the average boiling-point temperature of each fraction. With these values and the composition of the oils, oil vaporization was calculated by the computer program, and results were compared with values determined in the laboratory. Each experiment usually required four trials before good agreement between computer- and laboratory-derived K values was obtained.

K values for LPG and heavier hydrocarbons in reservoir oils are related to the volatility of the oils and to pressure and temperature. This relationship can be illustrated by referring to the Data Book by NGPSA and comparing K values for different convergence pressures. (The convergence pressure of a system is that pressure at which the K values of the various components converge toward a common value of unity.) At high pressures and temperatures, phase

TABLE 2—MOLE COMPOSITION CALCULATED FROM STOCK-TANK OIL DISTILLATION DATA FOR THREE OILS

Conditions of distillation			35° API oil					22° API oil	45° API oil
Distillation fraction	Reservoir oil fraction	Avg. boiling point, °F	Liquid volume distilled, percent	Liquid volume, percent of C_7+ components	Sp. Gr. of fraction, 60/60°F	Molecular weight of fraction	Mole percent of C_7+ components	Mole percent of C_7+ components	Mole percent of C_7+ components
Distillation loss----------------3.2									
1		99	-						
2		144	2.2		.693	84.			
3	9	189	6.2	6.55	.718	95	12.52	5.49	14.81
4	10	234	7.1	7.51	.744	108	13.09	6.89	14.89
5	11	279	5.7	6.02	.762	122	9.51	8.06	10.49
6	12	324	5.0	5.29	.779	136	7.66	4.35	8.95
7	13	369	4.5	4.76	.797	152	6.31	4.80	7.14
8	14	414	4.8	5.07	.813	168	6.20	5.83	6.69
9	15	459	4.6	4.86	.826	187	5.43	7.03	6.55
10	16	504	5.7	6.02	.837	207	6.16	8.89	7.01
Distillation continued at 40 mm. Hg									
11	17	369	2.7	2.85	.853	231	2.66	3.97	3.33
12	18	414	5.1	5.39	.867	258	4.99	8.88	5.40
13	19	459	4.8	5.07	.871	287	3.89	2.50	3.36
14	20	504	5.0	5.29	.889	317	3.75	4.79	3.15
15	21	549	4.3	4.55	.901	348	2.98	2.62	2.92
0.9 Residue	22		26.2	27.70	.952	500	13.34	23.34	4.80
.1 Residue	23		2.9	3.07	.952	500	1.51	2.56	0.51
Total			100.0	100.00			100.00	100.00	100.00

TABLE 3—MOLE PERCENT AND K VALUES OF FRACTIONS FOR 35° API-BASE RESERVOIR OILS

	1100 psia						2600 psia						4100 psia					
	100°F		175°F		250°F		100°F		175°F		250°F		100°F		175°F		250°F	
Fraction	Mole %	K*	Mole %	K*	Mole %	K*	Mole %	K*	Mole %	K*	Mole %	K*	Mole %	K	Mole %	K*	Mole %	K*
1	21.76	4.2494	18.06	4.8708	16.01	5.1203	39.70	2.2999	36.41	2.4359	34.75	2.4564	52.31	1.7171	49.75	1.7361	48.50	1.7292
2	5.00	.88	4.81	1.32	4.75	1.7	5.50	.77	5.45	.92	5.26	1.08	5.73	0.77	5.86	.882	5.62	.96
3	5.10	.36	5.04	.61	5.06	.94	4.89	.45	5.01	.57	4.87	0.72	4.69	.51	4.94	.64	4.73	.74
4	1.02	.192	1.02	.35	1.02	.575	.97	.295	.99	.375	.96	.51	.90	.37	.96	.536	.92	.59
5	3.18	.158	3.21	.28	3.26	.49	2.76	.259	2.90	.338	2.83	.45	2.44	.337	2.63	.47	2.53	.539
6	1.19	.075	1.23	.158	1.26	.296	.97	.168	.98	.234	1.00	.334	.76	.24	.80	.362	.81	.426
7	2.09	.066	2.17	.13	2.22	.262	1.62	.166	1.71	.197	1.74	.282	1.29	.206	1.38	.294	1.39	.388
8	5.36	.027	5.68	.06	5.86	.136	3.89	.069	4.14	.107	4.32	.175	2.88	.114	3.02	.202	3.19	.257
9	6.93	.0183	7.36	.0383	7.59	.0815	4.98	.0595	5.31	.097	5.55	.166	3.63	.198	3.84	.256	4.05	.340
10	7.23	.0089	7.69	.0202	7.92	.0465	5.20	.0316	5.55	.0579	5.79	.107	3.79	.112	4.01	.167	4.23	.247
11	5.26	.00438	5.59	.0105	5.76	.0262	3.78	.0167	4.03	.0339	4.21	.0692	2.76	.0628	2.92	.107	3.07	.183
12	4.24	.00197	4.50	.0053	4.64	.0146	3.04	.0080	3.25	.0187	3.39	.0428	2.22	.0333	2.35	.065	2.47	.125
13	3.49	.00086	3.71	.00258	3.82	.00772	2.51	.0039	2.68	.0097	2.79	.0249	1.83	.0168	1.93	.0362	2.04	.0796
14	3.43	.352E-3	3.65	.00112	3.76	.00365	2.47	.00164	2.63	.00451	2.75	.0131	1.80	.00746	1.90	.0187	2.01	.0462
15	3.01	.128E-3	3.20	.442E-3	3.29	.00153	2.16	.628E-3	2.31	.00195	2.41	.00623	1.58	.00307	1.67	.0090	1.76	.0257
16	3.41	.422E-4	3.63	.156E-3	3.74	.60E-3	2.45	.221E-3	2.62	.772E-3	2.73	.00272	1.79	.00118	1.89	.00385	1.99	.0122
17	1.47	.138E-4	1.56	.523E-4	1.61	.205E-3	1.06	.760E-4	1.13	.284E-3	1.18	.00109	.77	.418E-3	.92	.00158	.86	.00584
18	2.76	.422E-5	2.94	.171E-4	3.02	.701E-4	1.99	.256E-4	2.12	.980E-4	2.21	.395E-3	1.45	.150E-3	1.53	.594E-3	1.61	.00233
19	2.16	.131E-5	2.29	.516E-5	2.36	.205E-4	1.55	.890E-5	1.65	.345E-4	1.73	.136E-3	1.13	.560E-4	1.20	.229E-3	1.26	.88E-3
20	2.07	.375E-6	2.20	.156E-5	2.27	.644E-5	1.49	.277E-5	1.59	.114E-4	1.66	.462E-4	1.09	.200E-4	1.15	.878E-4	1.21	.326E-3
21	1.65	**.1E-6	1.75	.48tE-6	1.80	.207E-5	1.18	.870E-6	1.26	.336E-5	1.32	.156E-4	.86	.663E-5	.91	.287E-4	.96	.122E-3
22	7.37	**.1E-6	7.84	.144E-6	8.08	.658E-6	5.30	.264E-6	5.65	.120E-5	5.90	.545E-5	3.87	.218E-5	4.09	.100E-4	4.31	.446E-4
23	.82	**.1E-6	.87	**.1E-6	.90	**.1E-6	.59	**.1E-6	.63	**.1E-6	.65	**.1E-6	.43	**.1E-6	.45	**.1E-6	.48	**.1E-6
Total	100.00		100.00		100.00		100.00		100.00		100.00		100.00		100.00		100.00	
C_5+	63.94		67.86		69.90		46.18		49.24		51.33		34.93		35.86		37.70	
C_7+	55.30		58.78		60.56		39.75		42.41		44.27		29.00		30.66		32.31	
Conv. press, psia	20,000		20,000		20,000		16,000		20,000		20,000		20,000		13,000		15,000	

* "E-X" following a number indicates the number should be multiplied by 10^{-X}, as: 0.325E-3 = 0.000325.

** This value was arbitrarily selected as a lower limit.

TABLE 4—MOLE PERCENT AND K VALUES OF FRACTIONS FOR 22° AND 45° API OILS

	22° API Oil		45° API Oils					
	4100 psia and 250°F		1100 psia and 250°F		2600 psia and 175°F		4100 psia and 250°F	
Fraction	Mole %	K*	Mole %	K*	Mole %	K*	Mole %	K*
1	45.18	2.0612	13.83	4.8061	39.62	1.9581	55.33	1.2595
2	2.24	.96	9.21	1.7	10.24	.97	10.21	1.02
3	1.06	.74	10.11	.94	9.99	.637	9.24	.90
4	.29	.57	2.06	.575	1.92	.468	1.72	.82
5	.79	.52	6.57	.49	5.54	.42	4.67	.77
6	.55	.41	1.98	.296	1.33	.391	.93	.70
7	.85	.358	3.99	.262	2.66	.26	1.86	.66
8	2.37	.237	6.64	.136	3.68	.157	2.09	.52
9	2.54	.254	6.75	.0979	3.71	.147	2.07	.68
10	3.18	.185	6.79	.0558	3.72	.0872	2.08	.494
11	3.73	.137	4.79	.0314	2.63	.0511	1.46	.366
12	2.01	.093	4.08	.0175	2.24	.0281	1.25	.25
13	2.22	.060	3.26	.00928	1.79	.0147	1.00	.159
14	2.69	.0345	3.05	.00438	1.67	.00679	.93	.092
15	3.25	.0192	2.99	.00184	1.64	.00294	.91	.0515
16	4.09	.0091	3.19	.721E-3	1.75	.00116	.98	.0244
17	1.83	.0044	1.52	.246E-3	.83	.428E-3	.46	.0117
18	4.10	.0017	2.46	.842E-4	1.35	.148E-3	.75	.0047
19	1.15	.00066	1.54	.246E-4	.84	.520E-4	.47	.00178
20	2.22	.00024	1.44	.773E-5	.79	.171E-4	.44	.653E-3
21	1.70	.91E-4	1.33	.249E-5	.73	.550E-5	.41	.24E-3
22	10.76	**.333E-4	2.18	**.790E-6	1.20	**.180E-5	.67	**.892E-4
23	1.20	**.1E-6	.24	**.1E-6	.13	**.1E-6	.07	**.1E-6
Total	100.00		100.00		100.00		100.00	
C_5+	50.44		58.22		32.69		18.83	
C_7+	46.67		45.61		25.02		13.95	
Conv. press, psia	20,000		20,000		5,800		5,000	

* "E-X" following a number indicates the number should be multiplied by 10^{-X}, 0.91 E-4 = 0.000091.

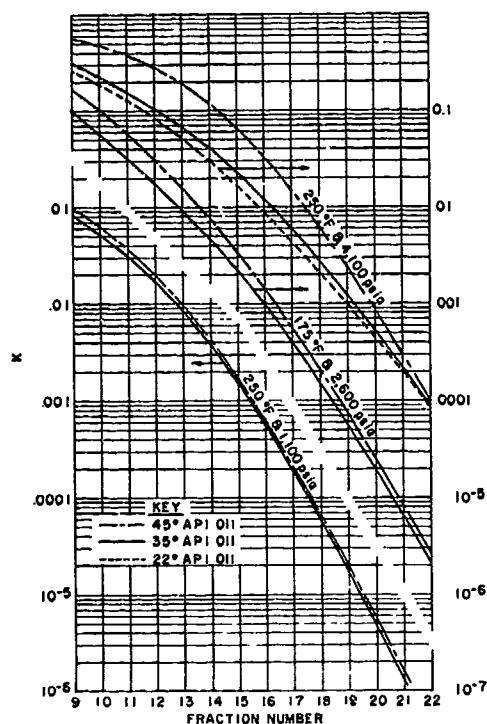** This value was arbitrarily selected as a lower limit.

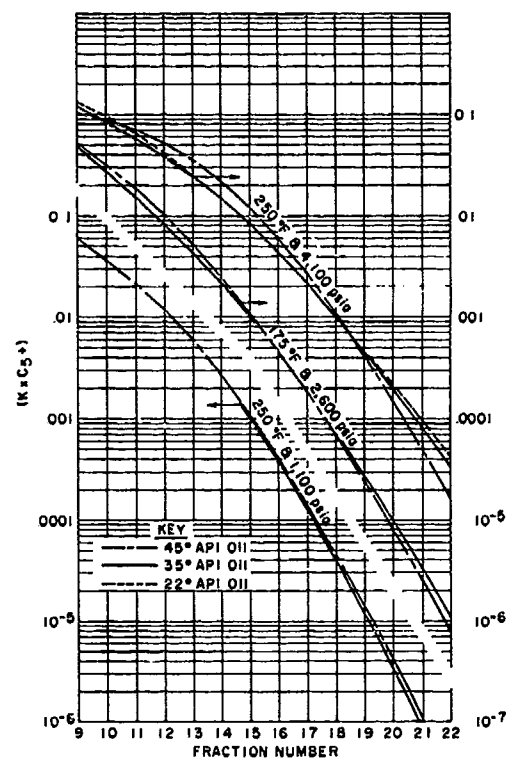Fig. 2—Comparison of K values for three different types of oils.

Fig. 3—Comparison of $(K \times C_5+)$ values for three different types of oil.

properties cannot generally be predicted with a great degree of confidence, especially if the liquid is highly volatile.

In this investigation, K values were found to be related to the volatility of the oil and to pressure and temperature. Three comparisons of K values for different types of oils (Fig. 2) show that K values of Fractions 9 through 22 increase considerably with increase in API gravity of the base oil.

An empirical method was found for selecting K values that would minimize the influence of type of oil. The volatility of a reservoir oil can be given a quantitative value if the volatility is considered a direct function of the mole fraction of all normally

gaseous components such as butanes and those components that are lighter. With this type of evaluation and with reference to Tables 3 and 4, which show the relative values for C_5+ reservoir oil, the volatility obviously increases as API gravity increases. The values of $K \times C_5+$ (K value times C_5+ mole fraction of reservoir oil) were found nearly equal for specific fractions of each of the three oils when compared at identical pressures and temperatures. The influence of oil type on $K \times C_5+$ is shown in Fig. 3. Although $K \times C_5+$ values are not in perfect agreement for the three oils, the discrepancy is not nearly so great as for K values (Fig. 2).

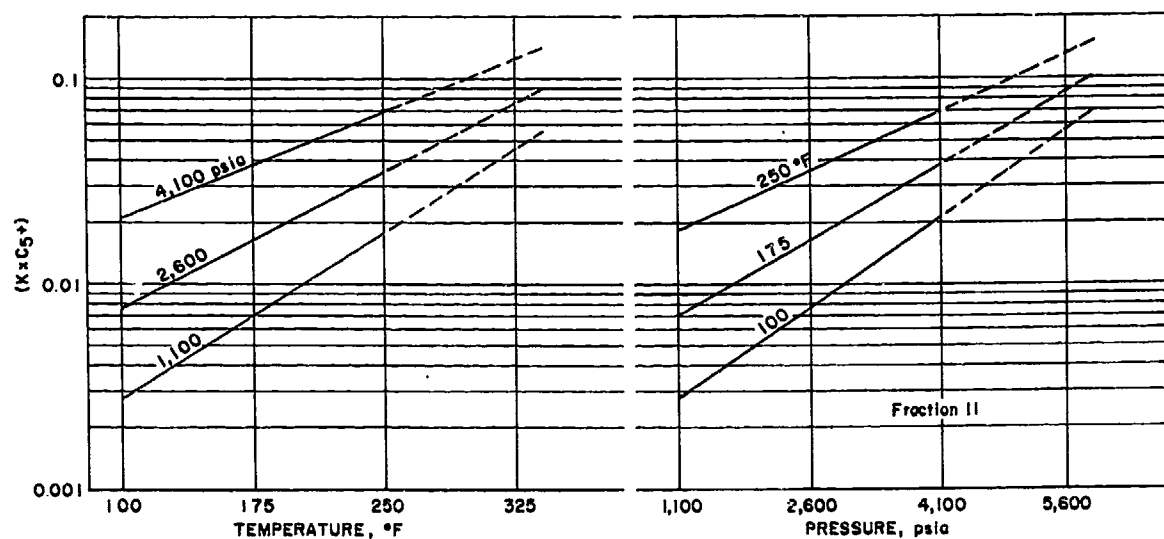By plotting and cross-plotting $K \times C_5+$ for Frac-

Fig. 4—Example showing correlation of $(K \times C_5+)$ values with temperature and pressure.

tions 9 through 22, a family relationship was established for the nine combinations of pressures and temperatures, considering all 13 experiments. The data were first plotted on semilog paper with $K \times C_5+$ vs fraction numbers. Next, values from these smoothed curves were plotted on semilog paper with $K \times C_5+$ vs both temperature and pressure. (The final results for Fraction 11 are shown in Fig. 4 as an example.) The final results for all fractions, shown as $K \times C_5+$ vs pressure, are given in Figs. 5 through 7.

The data shown in Figs. 5 through 7 were used in a standard statistical analysis (among other authors, see Mendenhall[12]) which resulted in a simple statistical model, or equation, relating log $(K \times C_5+)$

values, for the various oil fractions, with temperature and pressure as follows:

$$\log(K \times C_5+)_{F,T,P} = -A_0 + A_1\,T + A_2\,p - A_3\,Tp$$

where F is the oil-fraction number; A_0, A_1, A_2 and A_3 are constants for a particular oil fraction; T is temperature in °F, and p is pressure in psia. The sets of constants for the various oil fractions are shown in Table 5. After $\log(F \times C_5+)$ has been calculated for Fractions 9 through 22, for a desired reservoir system, K values can be obtained by dividing the antilog of $\log(K \times C_5+)$ by the mole fraction of C_5+ in the reservoir oil.
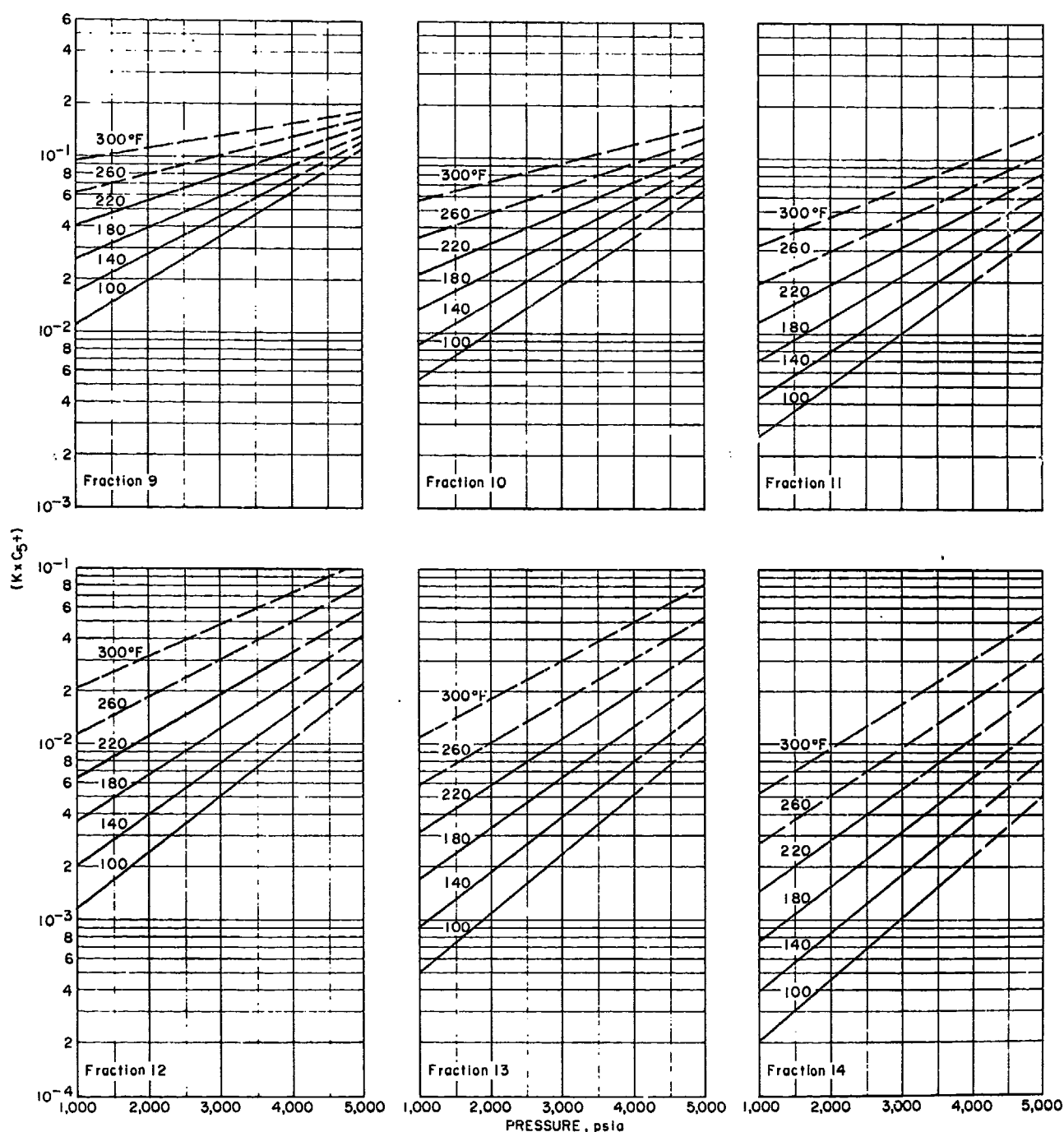

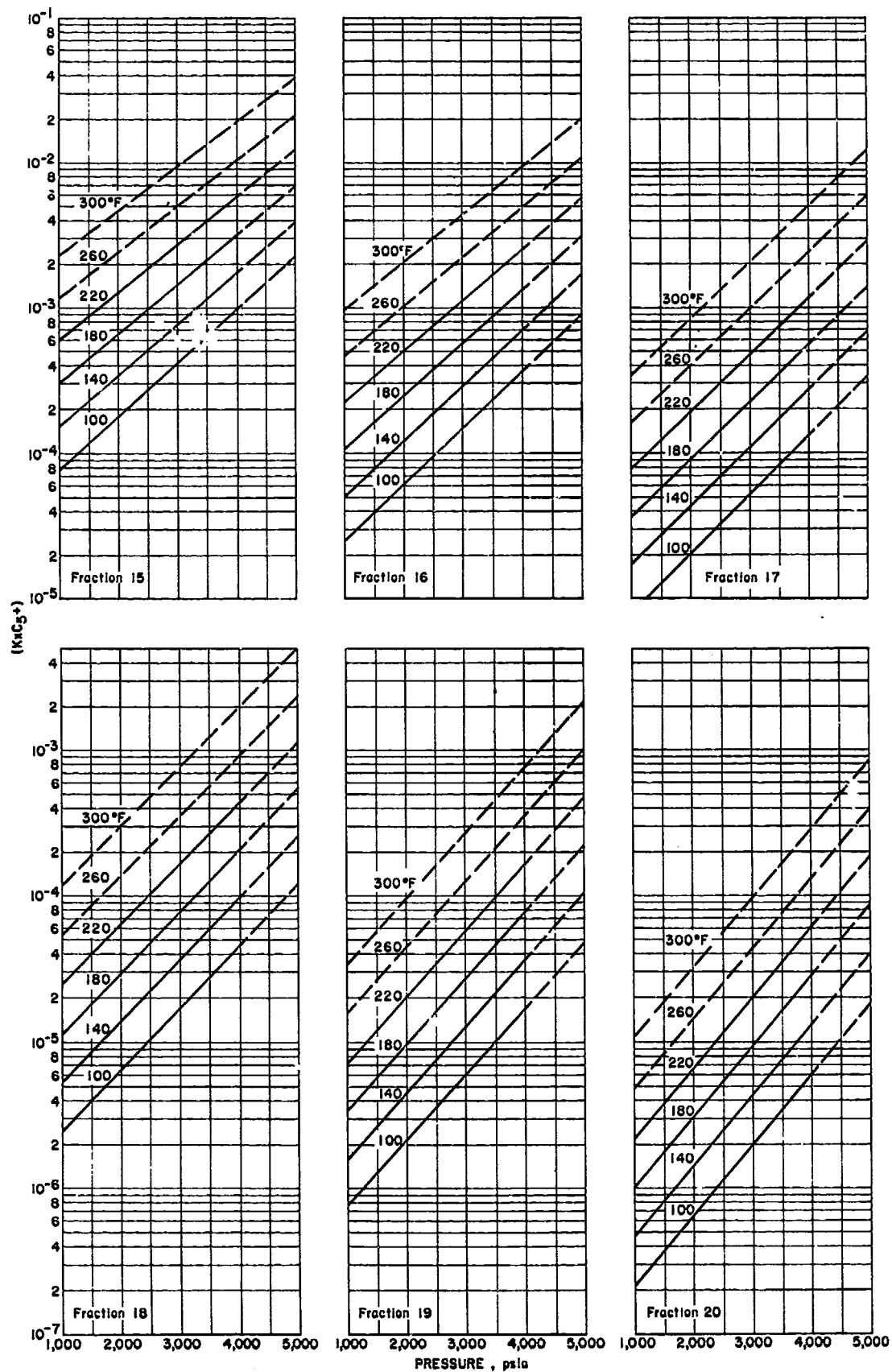Fig. 5—($K \times C_5+$) values for heptanes-plus Fractions 9 through 14.

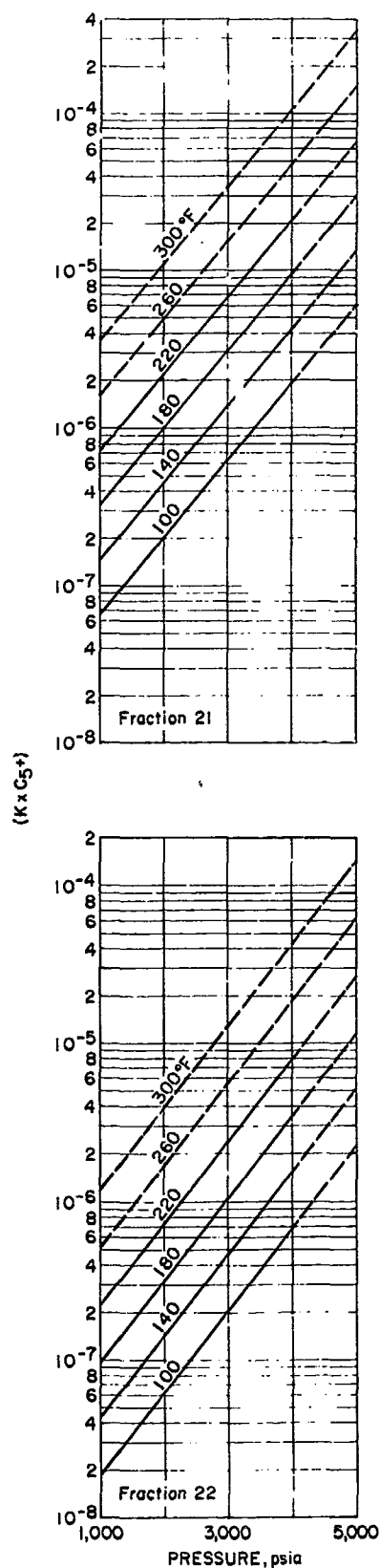**Fig. 6**—$(K \times C_5+)$ values for heptanes-plus Fractions 15 through 20.

K Values for Methane Through Hexanes

In selecting K values for the various components of the reservoir oils used in the 13 laboratory experiments we made the calculated saturation pressures of oils the same as the cycling pressures. To accomplish this, we referred to the section on Equilibrium Ratio in the *Engineering Data Book* by the NGPSA. As indicated on page 165 of that publication, if K_i is the K value of component i and m_i is the number of moles of a component i, the sample is liquid at its bubble point (saturation pressure) if summation of $K_i m_i$ is exactly equal to summation of m_i where i goes from 1 to n for a system containing n components. As the mole composition usually is expressed as mole fractions with the sum equaling 1.0, the summation of $K_i m_i$ must also equal 1.0.

The Data Book shows graphically a family of K-value curves for several convergence pressures. When there is a considerable difference between the saturation pressure of the oil and the convergence pressure of the system, the K values of methane increase considerably with increasing convergence pressures. Generally, Km for methane is greater than that for all other components combined. Thus, in a test for saturation pressure for a selected convergence pressure, if the summation of $K_i m_i$ is less than 1.0, a new and greater convergence pressure should be chosen. Thus, by trial and error, a convergence pressure can be found so that the summation of $K_i m_i$, including the small $K_i m_i$ values for the C_7+ fractions, will equal 1.0, and the saturation pressure will equal the cycling pressure. Following this reasoning, K values were selected for the components methane through hexanes so that the oil system would have the desired saturation pressure. (The highest convergence pressure shown in the Data Book was 20,000 psia. In some experiments with the low-volatility-type oils, this convergence pressure was too low for summation of $K_i m_i$ to equal 1.0. In those experiments, K values of ethane through hexanes were taken from the curves for the 20,000-psia convergence pressure, and the K values of methane were adjusted for the summation of the $K_i m_i$ to equal 1.0.)

When calculating convergence pressures, we do not consider the composition and amount of gas that is

Fig. 7—($K \times C_5+$) values for heptanes-plus Fractions 21 and 22.

TABLE 5—CONSTANTS FOR THE EQUATION RELATING LOG ($K \times C_5+$) VALUES FOR VARIOUS HEPTANES-PLUS OIL FRACTIONS WITH TEMPERATURE AND PRESSURE*

F	A_0	A_1	A_2	A_3
9	2.7675	5.5744×10^{-3}	3.4297×10^{-4}	9.0×10^{-7}
10	3.1400	5.9380×10^{-3}	3.5626×10^{-4}	8.1×10^{-7}
11	3.4941	6.1808×10^{-3}	3.6151×10^{-4}	6.7×10^{-7}
12	3.9251	6.7616×10^{-3}	3.8182×10^{-4}	6.4×10^{-7}
13	4.3595	7.2752×10^{-3}	3.9868×10^{-4}	6.0×10^{-7}
14	4.7890	7.5588×10^{-3}	3.9848×10^{-4}	4.8×10^{-7}
15	5.2701	7.7940×10^{-3}	4.0015×10^{-4}	3.2×10^{-7}
16	5.8244	8.2656×10^{-3}	4.1936×10^{-4}	2.9×10^{-7}
17	6.3106	8.1224×10^{-3}	4.0719×10^{-4}	4.0×10^{-8}
18	6.8811	8.4456×10^{-3}	4.3026×10^{-4}	4.0×10^{-8}
19	7.3930	8.1988×10^{-3}	4.5146×10^{-4}	.0
20	8.0010	8.4868×10^{-3}	4.8409×10^{-4}	.0
21	8.5978	8.8172×10^{-3}	5.0446×10^{-4}	.0
22	8.6701	7.4008×10^{-3}	4.3882×10^{-4}	.0

* log $(K \times C_5+)_{F,T,P} = -A_0 + A_1 T + A_2 P - A_3 TP$, where C_5+ is mole fraction of reservoir oil, F is the fraction number, and T and P are expressed in °F and psia, respectively.

transferred from one cell to another to be a part of the hydrocarbon system. After the gas has traveled only a short distance through a reservoir, it has passed through many pores in the reservoir rock. Thus, change in gas composition from one pore to the next is extremely small. Equilibrium is assumed in each pore so the gas entering a new pore is practically in equilibrium with oil in the pore. If exact equilibrium were reached, the amount of gas would be of no importance and could be zero; therefore, only the reservoir oil should be considered in determining the convergence pressure.

When the cycling pressure is higher than the saturation pressure, there is chance for more error in determining K values for reservoir conditions than when the pressures are the same. K values should be based on the composition of the reservoir oil at the gas-oil interface. At this location in the reservoir the oil will be saturated with gas and in equilibrium with the gas. Also, by the time the injection gas has traveled this far, it has become enriched with reservoir oil. Thus, the oil is in equilibrium with enriched gas, and the gas that dissolved in the oil to raise the oil's saturation pressure has also been enriched. Therefore, in calculating the composition of the oil, with the saturation pressure equal to cycling pressure, it should not be assumed that only dry gas has dissolved into the oil.

Laboratory Vaporization Experiments
Equipment

The equipment, which has been described fully,[7] consists of an internally chromium-plated steel tube packed with finely sifted Wilcox sand. The tube is approximately 44 in. long and has an ID of 1¾ in. The sand section has a void space of approximately 570 ml, a porosity of 32 percent, and a permeability to air of 4.3 darcies.

A unique feature of the laboratory reservoir permits the tube part to rotate at 1 rpm while the outlet and inlet heads are held stationary. The outlet end contains diametrically opposed windows for observation of the flowing fluids, and two valves, one on the top and the other at the bottom. Oil and free gas, when being produced simultaneously, can be separated by manipulating the two valves to keep a gas-oil interface in view through the windows. Thus, only gas is produced through the top valve and only oil flows through the bottom valve. The laboratory equipment was designed solely to study vaporization. This requires that the sand matrix be homogeneous for uniform oil displacement, that the oil be immobile, and that the gas flow through all parts of the reservoir. It also requires that the permeability be high enough so that inlet and outlet pressures are the same. Therefore, a uniform reservoir was made with dry, unconsolidated sand instead of with a consolidated sand core containing interstitial water.

Procedures and Discussion

Injecting and passing gas through the laboratory reservoir is called gas cycling, even though the produced gas is not reused. For these experiments, a lean gas containing less than 1 percent propane and only a trace of butanes and heavier gases was used. The

amount of vaporization is primarily determined by collecting condensate in a gas-oil separator operated at atmospheric pressure; but some of the products of vaporization, because they remain in the gaseous phase, must be determined from periodic gas analyses and measured volumes of produced gas. In this study, corrections were made to include all C_5+ hydrocarbons as stock-tank oil.

Pore volume is generally the unit of measurement for gas when discussing oil produced by gas displacement. But for this investigation pore volume would be an awkward unit because vaporization is more closely related to gas volumes at standard conditions. Instead, standard cubic feet per barrel of immobile stock-tank oil was used, with the gas being corrected to standard conditions of pressure and temperature. The immobile stock-tank oil was defined as containing the C_5+ components of the reservoir oil and is referred to as C_5+ stock-tank oil or, simply, stock-tank oil. C_5+ stock-tank oil was chosen for measuring the immobile oil because the stock-tank oil derived from a unit volume of reservoir oil is influenced by separator conditions of pressure and temperature and the amount of free gas being produced with the oil. Immobile oil was used instead of initial reservoir oil because it is the oil subjected to vaporization, and the minimum oil saturation (immobile oil) is not a constant for all reservoirs.

In the laboratory experiments, the period of two-phase flow was short enough so that the stock-tank oil produced last was essentially the same as that produced with no free gas. This occurred because all of the gas produced during the period of two-phase flow had become so enriched from the immobile oil near the inlet end as to be in near equilibrium with the initial reservoir oil near the outlet end. No vaporized products were derived from the oil produced during the period of two-phase flow; therefore, all of the vaporized oil resulted from the immobile oil. This may not occur in natural reservoirs, but this investigation was made to determine K values, which would be appropriate in either case.

In establishing the research project to determine oil vaporization, the plan was to investigate thoroughly the effects of pressure, temperature, and type of oil on oil vaporization. The conditions chosen for pressure, temperature, and stock-tank oil for synthesizing reservoir oils were 1,100, 2,600, and 4,100 psia; 100, 175, and 250°F; and 22.3°, 35.4°, and 45.2°API, respectively. (For simplicity, these oils are referred to in the text as 22°, 35°, and 45°API oil.) To investigate thoroughly all combinations of these pressures, temperatures, and types of oil would have required 27 experiments. Because of the time required to perform and evaluate data from each experiment, the laboratory work was terminated when 13 experiments had been completed. Nine of the experiments were conducted with the 35°API oil and covered all combinations of the three pressures and three temperatures. Three experiments were conducted with the 45°API oil for pressure and temperature combinations of 4,100 psia and 250°F, 2,600 psia and 175°F, and 1,100 psia and 250°F. Only one experiment was conducted with the 22°API

oil; pressure and temperature conditions were 4,100 psia and 250°F. These data are given in Tables 6 and 7. (Experimental details and data have been published.[13])

The pressure range below 1,100 psia is not covered in this paper because (1) most gas cycling is conducted at high pressures, (2) when gas is cycled at low pressures, the reservoir is usually shallow and therefore has a low temperature,* and (3) if it is desirable, vaporization at pressures up to 1,100 psia can be calculated with K values determined by the method described by Erbar et al.[14] K values thus determined for conditions of 1,100 psia and 175°F were found to compare favorably with those determined by the method given in this paper for oils of 35° and 45° API gravities.

Comparison of Computer-Calculated Data with Laboratory Data

We can test the validity of our K values by comparing laboratory data with the oil vaporization values determined by the computer method using these K values. (The K values used were those obtained for the equa-

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*For a reasonable cycling rate, the pressure would have to be several hundred psi. Also, at pressures between 100 and 1,100 psia, and at low temperatures, vaporization is insignificant.

TABLE 6—VAPORIZATION OF 35°API-BASE RESERVOIR OILS

Gas cycled, Mcf/STB	Immobile stock-tank oil vaporized, percent								
	1100 psia			2600 psia			4100 psia		
	100°F	175°F	250°F	100°F	175°F	250°F	100°F	175°F	250°F
2	0.93	3.65	6.35	2.63	5.61	8.30	8.23	12.25	15.15
4	2.30	7.23	12.30	5.41	10.35	15.39	14.40	19.93	25.50
6	3.77	10.16	16.79	8.06	14.19	20.62	18.97	25.36	32.29
8	5.16	12.70	20.12	10.47	17.50	24.46	22.46	29.60	36.82
10	6.22	15.10	23.50	12.46	20.51	28.11	25.02	33.00	40.40
12	7.48	17.05	26.15	14.69	22.99	31.01	27.28	35.55	43.15
14	8.76	18.74	28.21	16.49	25.13	33.29	29.06	37.54	45.21
16	9.96	20.07	29.83	18.28	26.86	35.13	30.46	38.97	46.83
18	11.01	21.22	31.09	19.89	28.36	36.61	31.61	40.12	48.09
20	11.87	22.19	32.21	21.26	29.61	37.89	32.47	40.89	49.01
22	12.56	23.03	33.16	22.47	30.73	38.99	33.16	41.53	49.76
24	13.21	23.83	33.99	23.58	31.73	39.92	33.71	42.03	50.29
26	13.80	24.50	34.85	24.51	32.61	40.81	34.00	42.40	50.65

TABLE 7—VAPORIZATION OF 22° AND 45° API RESERVOIR OILS

Gas cycled, Mcf/STB	Immobile stock-tank oil vaporized, percent			
	22°API Oil	45° API Oil		
	4100 psia and 250° F	1100 psia and 250° F	2600 psia and 175° F	4100 psia and 250° F
2	7.43	11.73	9.90	36.00
4	12.67	20.84	18.47	52.00
6	16.50	27.42	25.45	57.80
8	19.33	32.21	30.82	61.79
10	21.07	35.76	35.02	64.59
12	22.64	38.54	38.39	66.68
14	23.97	40.82	40.88	68.19
16	25.06	42.63	42.91	69.39
18	26.07	44.12	44.58	70.36
20	27.00	45.39	46.02	71.19
22	27.87	46.50	47.24	71.97
24	28.63	47.47	48.34	72.68
26	29.38	48.33	49.26	73.33
46.6 *				77.46
48.5 *	34.80			
67.0 *		57.41		
94.5 *			61.78	

* Terminal experimental value.

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tion in the footnote of Table 5 and not from K values determined by matching computed vaporization data and laboratory-derived vaporization data.) These comparisons are shown in Figs. 8 and 9. With reference to the figures, the first part of the curves is dominated by vaporization of pentanes, hexanes, and heptanes. After a small amount of gas cycling, all of these components are vaporized if the injection gas contains none of the components. Therefore, when consider-
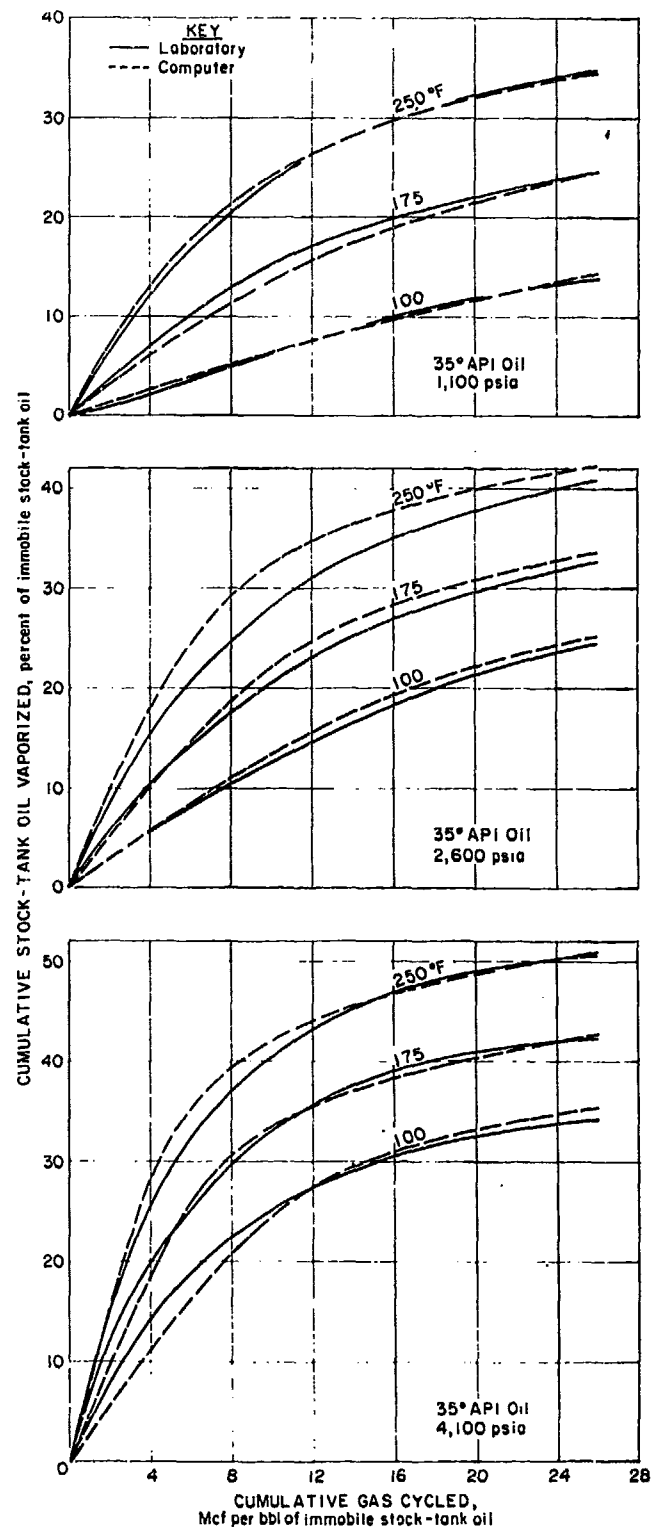

Fig. 8—Comparison of computer results with laboratory data.

ing only total oil vaporized, the shape of the first part of the curves becomes unimportant; it is the vaporization characteristics of the heavier components that determine the total amount of oil that will be vaporized.

To test the reliability of this method of calculating oil vaporization, refer to Table 8, which lists calculated and laboratory values for all 13 experiments at four different amounts of gas cycled per unit of immobile stock-tank oil: 8, 14, 20, and 26 Mcf/bbl. The maximum deviation, if we consider the amount of oil vaporized in the laboratory to be one unit, was 19.8 percent. This was for the 35° API oil at 2,600 psia and 250°F. The average deviation for the 52 comparisons was 4.9 percent, based upon percent vaporized. This average deviation amounts to only 1.6 percent of the total immobile stock-tank oil, or 0.64 percent of the initial oil in place (assuming an average of 40 percent immobile oil saturation).

A study of these comparisons shows that this method of calculating oil vaporization is subject to some error. However, errors in calculating oil vaporization probably will be smaller than other calculated values such as (1) volume of initial stock-tank oil in place, (2) sweep efficiency, and (3) immobile oil saturation, which are required to calculate total oil recovery by gas cycling. When considering these favorable comparisons, it should be remembered that by using only three different oils the effect of the type of oil as de-

scribed by the paraffin-aromatic ratio was not investigated. Thus, these comparisons may be optimistic.

Special Considerations

Although the main purpose of this paper is to explain a method for determining realistic K values for use in calculating oil vaporization, several pertinent problems were observed during the study.

Change in Oil Composition During Gas Cycling

Unlike conditions for only one PV cell, the percentage rate of vaporization for the individual components of the C_5+ oil, during the first part of gas cycling, is nearly a direct function of their K values. After a small amount of cycling, all of the component with the highest K value (pentane) is vaporized. Next, all of the hexane is vaporized, followed by all of the heptane, etc. This process is illustrated in Fig. 10, which shows the amounts of the fractions vaporized for eight different volumes of gas cycled.

Effect of Assuming C_7+ Oil as One Component in Vaporization Calculations

The importance of subdividing the C_7+ oil can be illustrated by comparing results of two calculations at 2,600 psia and 175°F for a 45° API oil in which (1) the C_7+ reservoir oil was considered to be lumped (one component) and (2) the C_7+ oil was subdivided
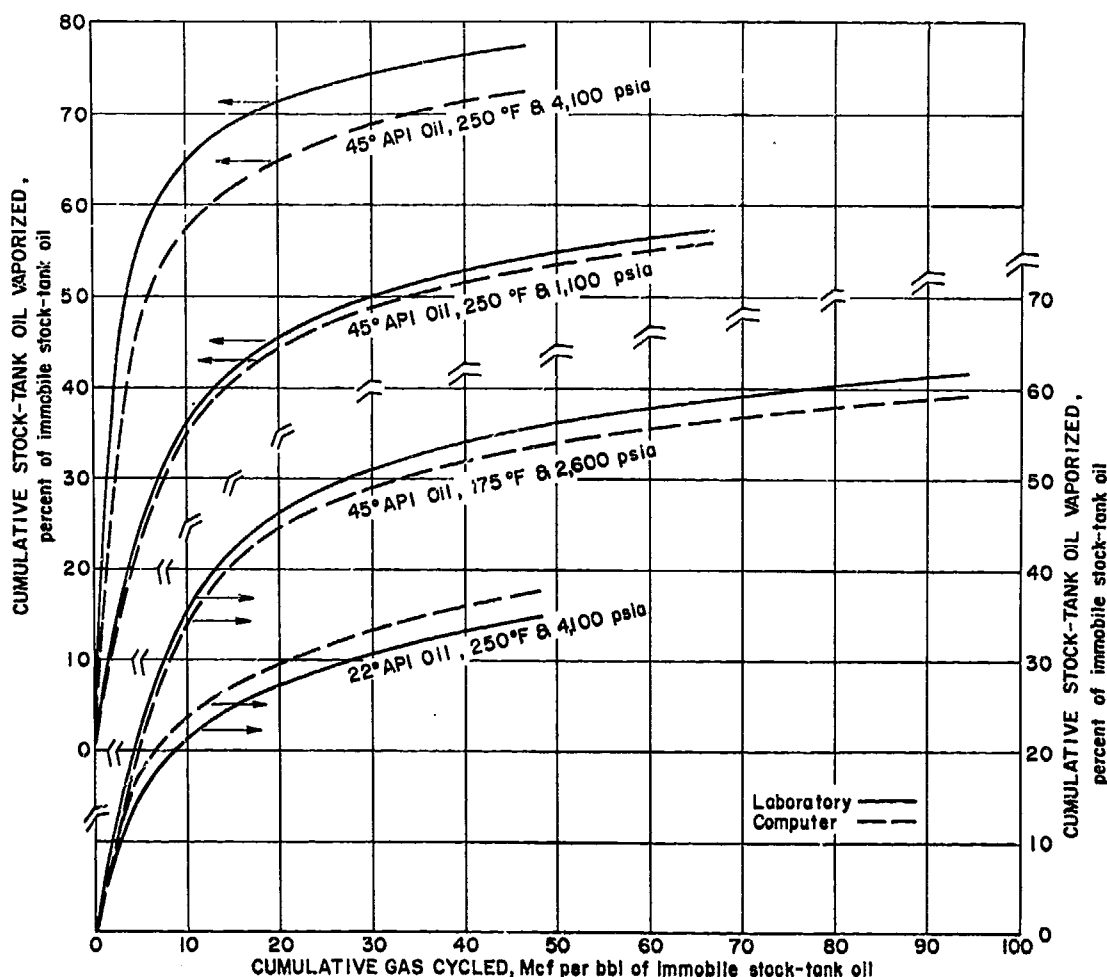

Fig. 9—Comparison of computer results with laboratory data.

TABLE 8—COMPARISON OF CALCULATED VAPORIZATION WITH LABORATORY DATA

Oil gravity, API	Press., psia	Temp, °F	Immobile stock-tank oil vaporized, percent Gas cycled, Mcf per bbl of immobile stock-tank oil												
			8			14			20			26		
			Lab.	Calc.	Dev., Percent	Lab.	Calc.	Dev., Percent	Lab.	Calc.	Dev., Percent	Lab.	Calc.	Dev., Percent
35	1100	100	5.16	5.25	1.7	8.76	8.68	0.9	11.87	11.73	1.2	13.80	14.40	4.3
	1100	175	12.70	11.30	11.0	18.74	17.34	7.5	22.19	21.52	3.0	24.50	24.42	.3
	1100	250	20.12	21.32	6.0	28.21	28.10	.4	32.21	31.95	.8	34.85	34.44	1.2
	2600	100	10.47	10.99	5.0	16.49	17.58	6.6	21.26	22.14	4.1	24.51	25.22	2.9
	2600	175	17.50	18.74	7.1	25.13	26.70	6.2	29.61	30.97	4.6	32.61	33.58	3.0
	2600	250	24.46	29.30	19.8	33.29	36.40	9.3	37.89	40.01	5.6	40.81	42.22	3.5
	4100	100	22.46	20.88	7.0	29.06	29.45	1.3	32.47	33.12	2.0	34.00	35.40	4.1
	4100	175	29.60	29.70	.3	37.54	37.11	1.1	40.89	40.40	1.2	42.40	42.35	.1
	4100	250	36.82	39.31	6.8	45.21	45.56	.8	49.01	48.68	.7	50.65	50.88	.5
22	4100	250	19.33	21.62	11.8	23.97	26.30	9.7	27.00	29.52	9.3	29.38	31.90	8.6
45	1100	250	32.21	30.65	4.8	40.82	39.44	3.4	45.39	44.02	3.0	48.33	47.15	2.4
	2600	175	30.82	29.25	5.1	40.88	39.33	3.8	46.02	44.14	4.1	49.26	47.34	3.9
	4100	250	61.79	54.30	12.1	68.19	60.97	10.6	71.19	64.60	9.3	73.33	67.20	8.4

Average deviation: 4.9 percent of the percent vaporized.

into 15 fractions. By the summation of $K_i m_i$ for the 15 fractions, a K value for the C_7+ lumped was calculated to be 0.0445. (The K value for Fraction 9, which has approximately the same boiling-point temperature as heptanes, was 0.097.) Curves giving results of these two calculation methods are shown in Fig. 11. The curve for the C_7+ subdivided is a near match for the laboratory data and shows that the rate of vaporization decreases considerably with the amount of gas cycled. The curve for the C_7+ lumped starts similarly to that for the C_7+ subdivided; but, after the heptanes have been vaporized, there is a great divergence between the curves, and the amount of vaporization for the C_7+ lumped is almost a straight-line relationship with gas cycled. The calculations indicate complete vaporization for a gas cycling value of about 12.5 Mcf/bbl or 2.5 PV for the C_7+ lumped. Perhaps more than 1,000 Mcf/bbl would be required to vaporize only 75 to 85 percent for the C_7+ subdivided. This illustrates the importance of recognizing that the volatility of the C_7+ fraction of reservoir oil decreases rapidly when gas is cycled through a reservoir and that selecting only one K value for C_7+ lumped oversimplifies the problem grossly.

Distribution of Residual Oil in a Linear Reservoir

More oil is vaporized at the inlet end of a linear reservoir (injection-well zone in a natural reservoir) than at other locations toward the outlet end. The dry gas first contacts the oil near the inlet end and vaporizes some of the components in the oil. This enriches the gas, which becomes increasingly richer as it continues through the reservoir. Thus, as gas passes through the reservoir, its ability to vaporize oil diminishes. Also, for a given oil and gas system, the percentage of oil vaporized is a function of the amount of gas contacting a unit volume of oil. Thus, on this basis, a unit volume of oil near the inlet end is contacted by many times more volumes of gas than the whole reservoir as a unit. Fig. 12 shows calculated relative volumes for residual oil and vaporized oil from the inlet to outlet ends of a linear reservoir. Cycling conditions were 2,600 psia and 175°F, using a 35°API gravity oil. The amount of gas cycled was 28 Mcf/bbl of immobile oil.
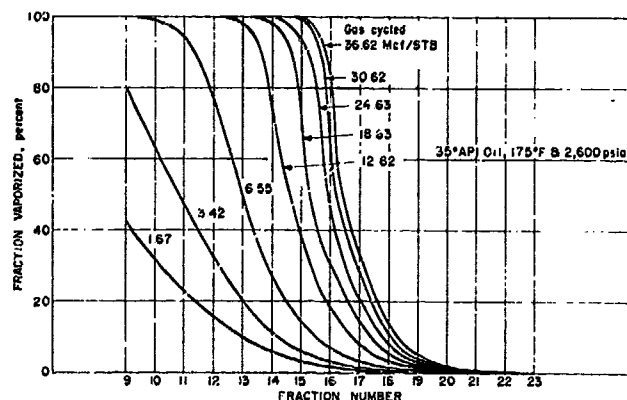

Fig. 10—Vaporization of heptanes-plus oil fractions during gas cycling.
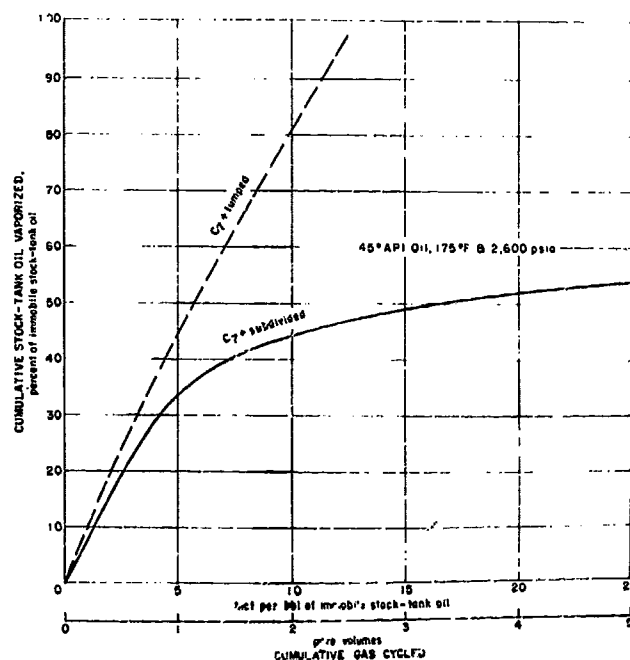

Fig. 11—Calculated vaporization with and without heptanes-plus lumped.

The shape of the curve in Fig. 12 will change for different systems of oil type, pressure, and temperature. Of the systems studied, Fig. 12 depicts approximately a medium one. For the one with the greatest oil vaporized (45°API oil, 4,100 psia, and 250°F), most of the oil was vaporized from the zone adjacent to the inlet. In one of the first calculations, the computer stopped before 120 loops were finished because all of the oil was shown to be vaporized in Cell 1. This was the reason for dividing the residuum (Table 2) into Fractions 22 and 23. Fraction 23 was arbitrarily given an extremely low K value, 1×10^{-7}, so that all of the oil in Cell 1 would not be vaporized from Cell 1. The other extreme in oil vaporization was for a system at 1,100 psia and 100°F. Under these adverse conditions of pressure and temperature, little of the C_7+ oil is vaporized in any of the cells. In fact, if the cycled gas is not extremely dry, more of the heavier gaseous components may be absorbed by the oil than are vaporized.

Cycling Raw Lease Gas Followed by Lean Processed Gas

Gasoline plants are often put on stream as soon as gas cycling projects are started. During the first few years of operation the recovery can be extremely profitable. However, during the latter part of gas cycling, gasoline plant yields will be considerably diminished. Because of this, calculations were made to determine the feasibility of cycling raw gas through most of the gas-cycling operations and installing a gasoline plant for use during the last few years only. Thus, the computer program was altered for cycling rich gas for 80 loops, followed by cycling dry gas for Loops 81 through 120, for a 35°API oil at 2,600 psia and 175°F. This permitted comparison with the regular program in which dry gas was used for cycling during 120 loops. Comparisons of calculated vaporization of reservoir oil for several different volumes of gas cycled are given in Table 9. Also shown in the table are the assumed compositions of both the dry and rich gases. (The calculations show that dry gas will produce slightly more oil through vaporization than the raw lease gas, but the opposite might occur because the addition of LPG components to dry gas tends to raise the K values for the heavier hydrocarbons and thus increase their volatility.) Installing a gasoline plant late in the life of the gas-cycling operations would have the advantage of re-

ducing the over-all cost of operating the gasoline plant. Although the plant products would not be available until a later date, there would be little disadvantage as far as total oil and gasoline plant liquid recoveries are concerned. However, it may be desirable to install a small-capacity gasoline plant for the first part of gas cycling operations to recover LPG components and natural gasoline from the stock-tank gas, and to install a low-pressure separator if two separators are used.

Summary and Conclusions

The composition of the C_7+ part of reservoir oil changes continuously during gas cycling. Thus, no one K value for C_7+ can be used to calculate oil vaporization accurately. To account for these changes, the C_7+ part of the reservoir oil was subdivided by USBM engineers into 15 fractions based upon distillation data on stock-tank oil. Then, by use of a computer program developed for this study, K values were established by the trial and error method for several oils at various pressures and temperatures, so that the calculated amount of vaporization matched that determined in the laboratory during 13 experiments.

K values also vary with composition of the original reservoir oil. In this study, the variation was accounted for by an empirical relationship in which it was found that $K \times C_5+$ mole fraction of reservoir oil was almost a constant for the various components of the reservoir oils investigated. Also, the data indicated a straight-line relationship for plots of $\log K \times C_5+$ vs both pressure and temperature. From these relationships an equation was derived for calculating K values for any condition of (1) composition of reservoir oil, (2) pressure, and (3) temperature. When comparing laboratory data with computed values, based upon K values calculated from the equation, the average deviation for 52 comparisons was only 4.9 percent.

Although K values of the 15 fractions of C_7+ reservoir oil were developed by linear models, they are intended for use for any normal field gas-cycling project and as a supplement to the normal calculating procedure for gas displacing oil.[15,16]

Gas cycling deep reservoirs with highly volatile oil, where the temperature is high and a high pressure can be maintained, could result in a much larger percentage oil recovery than could waterflooding. When considering both the oil displaced by gas and the vaporization of the immobile oil, the total recovery from the
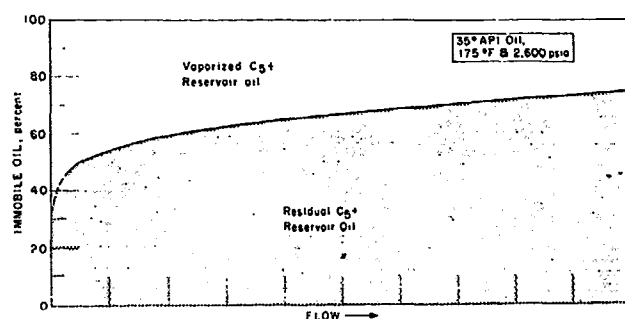

Fig. 12—Distribution of residual oil after gas cycling 28 Mcf/STB.

TABLE 9—COMPARISON OF VAPORIZATION BY DRY-GAS CYCLING WITH RICH-GAS CYCLING AND COMPOSITION OF THE TWO GASES

	Percent vaporized				
Loop	Dry Gas	Rich Gas	Component	Dry Gas	Rich Gas
5	2.77	2.70	CH_4	0.9471	0.9312
10	5.59	5.44	C_2H_6	.0467	.0491
20	11.26	10.86	C_3H_8	.0062	.0136
40	20.68	19.97	C_4H_{10}	.0000	.0016
60	26.44	25.82	C_5H_{12}	.0000	.0045
80	29.94	29.38	Total	1.0000	1.0000
100	32.32	31.91 *			
120	34.09	33.77 *			

* Rich-gas cycling was discontinued after loop 80 and followed by dry-gas cycling.

flow path of the gas could be exceptionally high, with 75 to 90 percent being normal. With the simple method presented here for calculating vaporization, and with laboratory data indicating which conditions of pressure and temperature and type of oil are favorable for large amounts of vaporization, the feasibility of gas cycling should be given more consideration.

References

1. McGraw, J. H. and Lohec, R. E.: "The Pickton Field—Review of a Successful Gas Injection Project", *J. Pet. Tech.* (April, 1964) 399-405.
2. Meltzer, B. D., Hurdle, J. M. and Cassingham, R. W.: "An Efficient Gas Displacement Project—Raleigh Field, Mississippi", *J. Pet. Tech.* (May, 1965) 509-514.
3. Simm, C. N.: "Recovery of Liquid Hydrocarbons by Gas Cycling Semidepleted Dark Oil Sands", *Oil & Gas J.* (Dec. 7, 1953) **52,** No. 31, 104.
4. Jacoby, R. H. and Berry, V. J., Jr.: "A Method for Predicting Pressure Maintenance Performance for Reservoirs Producing Volatile Crude Oil", *Trans.,* AIME (1958) **213,** 59-64.
5. Attra, H. D.: "Nonequilibrium Gas Displacement Calculations", *Soc. Pet. Eng. J.* (Sept., 1961) 130-136.
6. McFarlane, R. C., Mueller, T. D. and Miller, F. G.: "Unsteady-State Distributions of Fluid Compositions in Two-Phase Petroleum Reservoirs Undergoing Gas Injection", *Soc. Pet. Eng. J.* (March, 1967) 61-74.
7. Cook, Alton B., Coulter, R. H., Jr., and Spencer, G. B.: "A Rotating Model Oil Reservoir for Simulating Gas-Cycling Operations", RI 5478, USBM (1959).
8. Katz, D. L., Cornell, D., Kobayashi, R., Poettmann, F. H., Vary, J. A., Elenbaas, J. R. and Weinaug, C. F.: *Handbook of Natural Gas Engineering,* McGraw-Hill Book Co., Inc., New York (1959) 258.
9. Smith, N. A. C., Smith, H. M., Blade, O. C. and Garton, E. L.: "The Bureau of Mines Routine Method for Analysis of Crude Petroleum. I. The Analytical Method", *Bull. 490,* USBM (1951).
10. Eilerts, C. K., *et al.*:"Phase Relations of Gas-Condensate Fluids", *Monograph 10,* USBM (1957) **1,** 393.
11. *Engineering Data Book,* Natural Gas Processors Suppliers Assn., 7th Ed. (1957).
12. Mendenhall, William: *Introduction to Linear Models and the Design and Analysis of Experiments,* Wadsworth Publishing Company, Inc., Belmont, Calif. (1968) 465 pp.
13. Cook, A. B., Johnson, F. S., Spencer, G. B., Bayazeed, A. F. and Walker, C. J.: "Effects of Pressure, Temperature, and Type of Oil on Vaporization of Oil During Gas Cycling", RI 7278, USBM (1969).
14. Erbar, J. H., Persyn, C. L. and Edmister, W. C.: "Enthalpies and *K*-Ratios for Hydrocarbon Mixtures by New Improved Computer Program", *Proc.,* Natl. Gas Proc. Assn. (1964) 26-34.
15. Price, H. S. and Donohue, D. A. T.: "Isothermal Displacement Processes With Interphase Mass Transfer", *Soc. Pet. Eng. J.* (June, 1967) 205-220.
16. Dorsey, J. B. and Brinkley, T. W.: "Performance Review of Shoats Creek Unit Vaporizing Gas-Drive Project", *J. Pet. Tech.* (April, 1968) 416-422. **JPT**