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Reservoir Fluid Study
Warn State Well No. 11
Vacuum Filed
Lea County
New Mexico

Summary

A reservoir fluid study was performed at the Petroleum Technology Center on separator gas and liquid samples taken from the Warn State No. 11 well. This report contains the following sections:

- Summary of sampling conditions
- Sample quality
- Compositional analysis of the separator gas and liquid
- Calculation of the Gas-Oil Ratio (GOR)
- Recombination of the separator fluids to the specified GOR
- Constant Composition Expansion (CCE) results
- Differential Vaporization results
- Solubility / Swelling and Viscosity Test results
- Separator Test results
- Minimum Miscibility Pressure (MMP) results

Sampling Conditions

Separator gas and liquid samples were obtained from the subject well on December 22, 1992 by a representative of Core Laboratories. Reported field and sampling data are given in Table 1. Reservoir conditions were obtained from M. T. Wiskofske, Midland. Samples were received at PTC on December 30, 1992.

Sample Quality

The opening pressure of the separator gas samples and the room temperature bubble point pressure of the separator liquid samples were determined as a quality check. As a result, gas cylinder no. K18231 and liquid cylinder no. 349007D were found to be most representative of separator conditions. These separator samples were used for the recombination mixture. All data reported here were obtained using these specific gas and liquid separator products.

Analysis of Fluid Compositions

The compositions of the separator gas and liquid were analyzed using gas chromatography. Table 2 shows the composition of the separator gas. Table 3 shows the composition of the separator liquid. The separator liquid composition was pieced together from GC results for the pressurized liquid sample and an atmospherically stabilized sample created in the lab.

Please note that the mass percent values given in the tables are the directly measured values. The mole percent values are back-calculated using the reported molecular weights.

The molecular weights and specific gravities of the hexanes-plus carbon number fractions were not directly measured but rather inferred to match the measured molecular weight and standard liquid density (at 60 °F) of the stabilized liquid sample. These values are presented with the mass distributions of each fluid sample in Tables 2 to 5. It was found that normal paraffin molecular weights reproduced the measured stabilized liquid sample molecular weight remarkably well. The specific gravity values were estimated assuming each fraction had the same Watson K Factor of 11.67. (This value was chosen to match the measured liquid density at 60 °F of the stabilized liquid sample.)

Calculation of the Gas Oil Ratio

The actual gas and liquid flow rates during sampling were not reported. Instead, we were asked to recombine the samples to a GOR of 750 scf/stb. To calculate the liquid flow rate at the separator, we measure the shrinkage factor by flashing the separator liquid to atmospheric conditions. The measured shrinkage factor is 1.019 sep bbl/stb, giving a field GOR of 736 scf/sep bbl. The GOR of the separator liquid flashed to 12 psia and 82 °F is 24 scf/stb. The gravity of the stock tank liquid is 38.5 °API at 60 °F.

Recombination of the Separator Fluids

The separator samples were recombined to a GOR of 736 scf/sep bbl. This single batch of recombined fluid was used for all of the phase behavior work reported here, including the minimum miscibility pressure measurements.

Table 4 contains the calculated composition of the recombined fluid.

Simulated distillation was performed on the stabilized liquid sample to give a carbon number distribution down to C30+. This distribution as corrected for the recombined fluid is given in Table 5, including the estimated molecular weights and specific gravities for all of the carbon number fractions.

Constant Composition Expansion

A portion of the recombined fluid was injected into PTC's large volume, high pressure PVT cell (Temco cell). A constant composition expansion (CCE) test was performed at 140 °F. The bubble point pressure of the fluid was found to be 2354 psia. The measured pressure vs. volume relationship of the recombined reservoir fluid obtained during the CCE is given in Table 6. This same data is also shown in Figure 1. No smoothing has been done to this data.

Differential Vaporization

Upon completion of the CCE test, the fluid in the Temco PVT cell was repressurized above the bubble point pressure and a differential vaporization (DV) test was performed. At each depletion pressure, the volumes of gas and liquid were measured. The gas was pushed from the PVT cell at constant pressure. At the higher pressures, the gas was collected in evacuated cylinders and the mass of gas collected was measured. At the lower pressures, the gas was flashed to atmospheric pressure and collected in the DBR Gasometer. The volume of gas collected and the mass of produced liquids were measured. The density at 60 °F of the final depletion liquid was measured in a Paar densimeter.

The data from the DV test is given in Table 7. The data for the pressures above the bubble point are from the CCE test. The specific gravities of the depleted gas were calculated from the compositions of the gases (see Table 8 for these compositions). The compressibility factors listed were first smoothed with respect to pressure before using to back calculate the mass and moles of depleted gas corresponding with the measured volumes. The oil density at each depletion step was calculated using the measured oil volume and the back calculated mass of oil remaining in the cell. The final volume of oil at ambient conditions was not directly measured but calculated using the measured density and the back calculated mass of residual oil. The oil formation volume factor and solution gas-oil ratio data are depicted in Figures 2 and 3, respectively.

Other than the evolved gas compressibility factors, no smoothing has been done to the measured data.

CO_2 Swelling and Viscosity Tests

A portion of the recombined fluid was then injected into PTC's low volume, high pressure PVT cell (DBR cell). The saturation pressure at the reservoir temperature was measured to ensure consistency with the previous results. Carbon dioxide (CO_2) was added. Mini-CCE tests were conducted to determine the saturation pressure and volume of the oil-CO_2 mixtures. After the saturation pressures were determined, the pressure was boosted to about 100 psi above the saturation pressure to measure the viscosity in the capillary viscometer.

This data is presented in Table 9 and depicted in Figures 4 to 6.

No smoothing was done to the data.

Minimum Miscibility Pressure Measurements

A portion of the recombined fluid was given to the RBA (Rising Bubble Apparatus) lab to determine the Minimum Miscibility Pressure (MMP) of the oil at various stages of depletion with respect to CO_2. For the first test, the recombined oil sample was charged to the sight gauge within the RBA and the MMP test performed. For each succeeding test, the oil sample was pressure depleted before performing the MMP test. (The pressure on the oil was slowly lowered below the bubble point, depleting the gas as it came out of solution).

The MMP data is presented in Table 10. No smoothing was done to the data.

Separator Test

A portion of the recombined fluid was injected into a low pressure separator at 43 psia and 65 °F and allowed to come to equilibrium. The volumes of gas and oil formed were measured. The composition of the gas was determined via gas chromatography. The results of this test are given in Table 11.

Table 1. Field Data for Reservoir Fluid Study

Well Record

Well	Warn State No. 11
Field	Vacuum
Formation	Drinkard
County	Lea
State	New Mexico

Reservoir and Well Characteristics

Reservoir Temperature	140	°F
Reservoir Pressure	2950	psia

Sampling Conditions

Well Testing Company	Core Laboratories	
Date Sampled	December 22, 1993	
Standard Temperature	60	°F
Standard Pressure	14.73	psia
Sampling Time		
Separator Temperature	65	°F
Separator Pressure	28	psig

Gas Oil Ratio

Field Gas Oil Ratio	750	scf/stb
Laboratory Shrinkage Factor	1.019	sep bbl/stb
Gas Oil Ratio	736	scf/sep bbl

Table 2. Separator Gas Composition

Component	Mass Percent	Mole Percent	Molecular Weight
Nitrogen	2.89	2.62	
Carbon Dioxide	2.61	1.51	
Methane	38.95	61.64	
Ethane	19.60	16.55	
Propane	19.72	11.35	
i-Butane	2.63	1.15	
n-Butane	7.39	3.23	
i-Pentane	1.80	0.63	
n-Pentane	1.74	0.61	
Hexanes	1.10	0.32	86.2
Heptanes	1.20	0.30	100.2
Octanes	0.34	0.08	114.2
Nonanes	0.01	0.00	128.3
Total	99.98	99.99	25.4
C6+	2.65	0.70	95.4
C7+	1.55	0.38	103.1

Table 3. Separator Liquid Composition

Component	Mass Percent	Mole Percent	Molecular Weight	Specific Gravity
Nitrogen	0.00	0.00		
Carbon Dioxide	0.01	0.04		
Methane	0.09	1.01		
Ethane	0.10	0.59		
Propane	0.80	3.17		
i-Butane	0.30	0.90		
n-Butane	1.30	3.91		
i-Pentane	0.89	2.15		
n-Pentane	1.21	2.92		
Hexanes	2.46	4.98	86.2	0.7256
Heptanes	7.17	12.48	100.2	0.7450
Octanes	8.53	13.03	114.2	0.7614
Nonanes	5.81	7.90	128.3	0.7777
Decanes	4.95	6.07	142.3	0.7922
Undecanes	4.12	4.60	156.3	0.8049
Dodecanes	4.11	4.21	170.3	0.8170
Tridecanes	4.22	3.99	184.4	0.8275
Tetradecanes	4.01	3.52	198.4	0.8380
Pentadecanes-Plus	49.89	24.54	355.0	0.9183
Total	99.97	100.01	174.4	0.8290
C6+	95.27	85.32	194.9	0.8483
C7+	92.81	80.34	201.6	0.8522
C12+	62.23	36.26	299.6	0.8987

Table 4. Recombined Fluid Composition

	Separator Gas	Separator Liquid	Recombined Fluid			
Component	Mass Percent	Mass Percent	Mass Percent	Mole Percent	Molecular Weight	Specific Gravity
Nitrogen	2.89	0.00	0.42	1.42		
Carbon Dioxide	2.81	0.01	0.39	0.83		
Methane	38.95	0.09	5.78	33.82		
Ethane	19.60	0.10	2.96	9.23		
Propane	19.72	0.80	3.57	7.60		
I-Butane	2.63	0.30	0.64	1.04		
N-Butane	7.39	1.30	2.19	3.54		
I-Pentane	1.80	0.89	1.02	1.33		
N-Pentane	1.74	1.21	1.29	1.67		
Hexanes	1.10	2.46	2.26	2.46	86.2	0.7256
Heptanes	1.20	7.17	6.30	5.89	100.2	0.7450
Octanes	0.34	8.53	7.33	6.02	114.2	0.7614
Nonanes	0.01	5.81	4.96	3.63	128.3	0.7777
Decanes		4.95	4.23	2.79	142.3	0.7922
Undecanes		4.12	3.52	2.11	156.3	0.8049
Dodecanes		4.11	3.51	1.93	170.3	0.8170
Tridecanes		4.22	3.60	1.83	184.4	0.8275
Tetradecanes		4.01	3.42	1.62	198.4	0.8380
Pentadecanes-Plus		49.89	42.59	11.26	355.1	0.9183
Total	99.98	99.97	99.98	100.02	93.8	0.7112
C6+	2.65	95.27	81.72	39.54	193.9	0.8477
C7+	1.55	92.81	79.46	37.08	201.1	0.8518
C12+	0.00	62.23	53.12	16.64	299.6	0.8987
Mass Fraction	0.1465	0.8535				

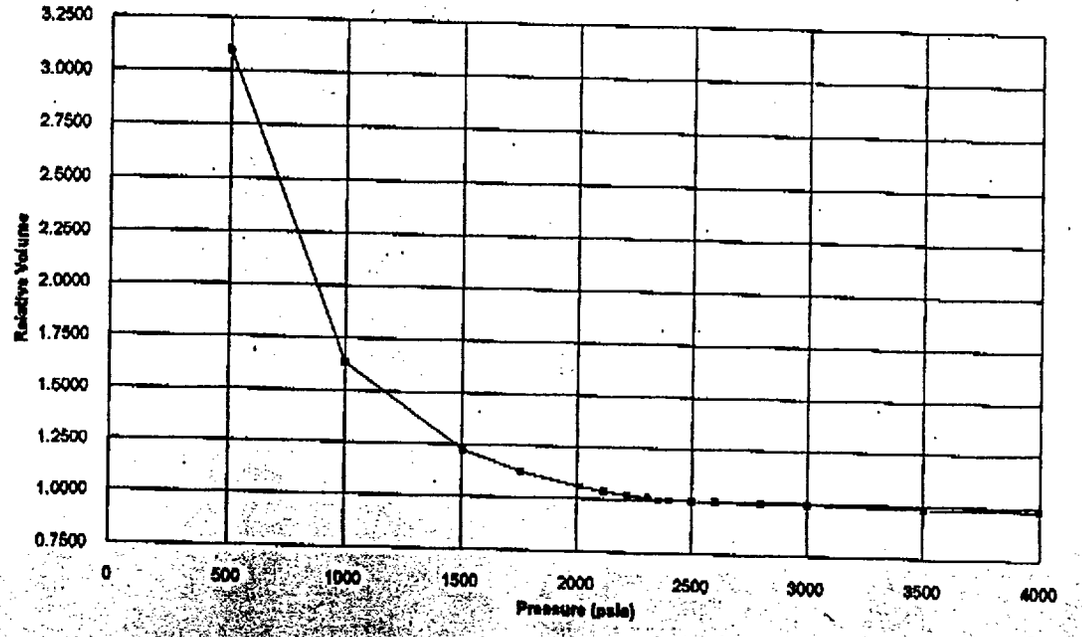
Table 5. Simulated Distillation and Estimated Properties for the Hexanes-Plus Fraction of the Recombined Fluid

Fraction	Incremental Amount	Cumulative Amount	Initial BPT (°F)	Final BPT (°F)	Average BPT (°F)	Molecular Weight	Specific Gravity
C6	2.77	2.77	97.8	156.6	147.5	86.2	0.7256
C7	7.70	10.47	156.6	210.1	197.5	100.2	0.7450
C8	8.97	19.44	210.1	259.1	242.0	114.2	0.7614
C9	6.07	25.51	259.1	304.4	288.0	128.3	0.7777
C10	5.17	30.68	304.4	346.4	330.5	142.3	0.7922
C11	4.30	34.98	346.4	385.6	369.0	156.3	0.8049
C12	4.30	39.28	385.6	422.3	407.0	170.3	0.8170
C13	4.41	43.69	422.3	456.7	441.0	184.4	0.8275
C14	4.19	47.88	456.7	489.3	475.5	198.4	0.8380
C15	3.29	51.17	489.3	520.1	511.0	212.4	0.8484
C16	3.37	54.54	520.1	549.3	542.0	226.5	0.8574
C17	3.10	57.64	549.3	576.5	572.0	240.5	0.8658
C18	2.70	60.34	576.5	602.2	595.0	254.5	0.8722
C19	2.73	63.07	602.2	626.7	617.0	268.5	0.8783
C20	2.48	65.55	626.7	651.7	640.5	282.6	0.8846
C21	2.30	67.85	651.7	674.6	663.2	296.6	0.8906
C22	2.13	69.98	674.6	696.4	685.5	310.6	0.8965
C23	2.08	72.06	696.4	717.1	706.8	324.6	0.9020
C24	1.98	74.04	717.1	737.1	727.1	338.7	0.9072
C25	2.01	76.05	737.1	756.1	746.6	352.7	0.9122
C26	1.71	77.76	756.1	774.5	765.3	366.7	0.9169
C27	1.80	79.56	774.5	792.3	783.4	380.8	0.9214
C28	1.58	81.14	792.3	809.2	800.8	394.8	0.9256
C29	1.59	82.73	809.2	825.6	817.4	408.8	0.9297
C30+	17.26	99.99	825.6	841.5	1074.0	715.7	0.9882

Table 6. Constant Composition Expansion at 140 °F

Pressure (psia)	Relative Volume[1]	Oil Density (g/cm³)
3998	0.9831	0.7052
3505	0.9854	0.7036
3002	0.9913	0.6994
2799	0.9944	0.6972
2600	0.9969	0.6955
2500	0.9982	0.6945
2400	0.9994	0.6938
2354 *Bubble Point*	1.0000	0.6933
2307	1.0068	
2214	1.0202	
2114	1.0369	
2014	1.0568	
1756	1.1237	
1506	1.2231	
1001	1.6367	
501	3.0956	

Figure 1. Constant Composition Expansion at 140 °F



[1] V/V_{sat} is the total volume of the fluid (oil and gas) at the indicated pressure per volume of the saturated oil at the bubble point pressure.

Table 7. Differential Vaporization Test at 140 °F

Pressure (psia)	Solution Gas/Oil Ratio[1]	Relative Oil Volume[2]	Relative Total Volume[3]	Oil Density (g/cm³)	Oil Specific Gravity[4]	Gas Density (g/cm³)	Gas Compressibility Factor (Z)	Gas Formation Volume Factor[5] (res bbl/MMscf)	Gas Specific Gravity[6]
3998		1.454	1.454	0.7052	0.7059				
3505		1.458	1.458	0.7036	0.7043				
3002		1.467	1.467	0.6994	0.7001				
2799		1.471	1.471	0.6972	0.6979				
2600		1.475	1.475	0.6955	0.6962				
2500		1.477	1.477	0.6945	0.6952				
2400		1.478	1.478	0.6938	0.6944				
2353 *Bubble Point*	738	1.479	1.479	0.6933	0.6940				
2002	641	1.439	1.569	0.6974	0.6981	0.172	0.636	960.8	0.7555
1501	534	1.407	1.606	0.6970	0.6977	0.112	0.706	1,423	0.7313
1000	415	1.311	1.673	0.7299	0.7307	0.0664	0.790	2,392	0.7273
500	289	1.274	2.136	0.7296	0.7303	0.0318	0.888	5,380	0.7628
200	201	1.266	2.836	0.7162	0.7170	0.0143	0.953	14,390	0.9415
99	156	1.237	2.635	0.7237	0.7244	0.00834	0.977	29,720	1.1352
12	0	1.049	40.248	0.7983	0.7991	0.00148	0.997	251,400	1.7094
12		1.000		0.8373	0.8381				

[1] R_s, ideal gas ft³ at 14.73 psia and 60 °F per barrel of residual oil at 60 °F.
[2] B_o, barrels of oil at indicated pressure and reservoir temperature per barrel of residual oil at 60 °F.
[3] B_t, barrels of oil plus liberated gas at indicated pressure and temperature per barrel of residual oil at 60 °F.
[4] The oil density, ρ_o, divided by the standard density of water at 60 °F, 0.999015 g/cm³.
[5] B_g, barrels of gas at indicated pressure and temperature per million ft³ of ideal gas at 14.73 psia and 60 °F.
[6] γ_g, ratio of the molecular weight of the gas to that of air, 28.9625.

Table 8. Compositions of Depletion Gases

Depletion Pressure (psia)	2002	1501	1000	500	200	99	14
Mole Percent:							
Nitrogen	6.25	5.07	3.24	1.57	0.54	0.17	0.00
Carbon Dioxide	1.26	1.35	1.49	1.84	2.09	1.99	0.65
Methane	75.57	76.81	76.85	70.22	52.43	31.67	4.61
Ethane	9.10	9.76	11.22	15.98	25.02	32.99	20.88
Propane	4.26	4.26	4.74	7.13	13.54	22.31	35.02
i-Butane	0.42	0.39	0.41	0.59	1.13	2.00	5.23
n-Butane	1.14	1.04	1.06	1.51	3.01	5.44	17.04
i-Pentane	0.29	0.25	0.23	0.31	0.59	1.06	4.20
n-Pentane	0.32	0.27	0.25	0.31	0.60	1.05	4.46
Hexanes	0.30	0.22	0.18	0.21	0.39	0.60	3.38
Heptanes	0.48	0.30	0.22	0.24	0.45	0.57	3.71
Octanes	0.35	0.18	0.10	0.10	0.18	0.15	0.79
Nonanes	0.15	0.07	0.02	0.01	0.03	0.01	0.03
Decanes	0.08	0.04	0.00	0.00	0.00	0.00	0.00
Undecanes	0.03	0.00	0.00	0.00	0.00	0.00	0.00
Dodecanes	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Mass Percent:							
Nitrogen	6.01	6.71	4.31	1.94	0.56	0.14	0.00
Carbon Dioxide	2.53	2.81	3.12	3.56	3.38	2.67	0.58
Methane	55.41	58.18	58.53	49.69	30.85	15.48	1.49
Ethane	12.51	13.86	16.01	21.19	27.60	30.17	12.68
Propane	8.58	8.86	9.92	13.86	21.89	29.92	31.20
i-Butane	1.11	1.08	1.13	1.50	2.41	3.53	6.14
n-Butane	3.03	2.86	2.93	3.86	6.41	9.61	20.00
i-Pentane	0.97	0.86	0.80	0.98	1.56	2.33	6.12
n-Pentane	1.06	0.91	0.84	1.00	1.59	2.31	6.50
Hexanes	1.20	0.89	0.72	0.79	1.23	1.56	5.88
Heptanes	2.18	1.39	1.03	1.06	1.66	1.74	7.52
Octanes	1.82	0.95	0.52	0.51	0.74	0.51	1.82
Nonanes	0.86	0.39	0.11	0.06	0.13	0.05	0.07
Decanes	0.49	0.24	0.01	0.01	0.00	0.00	0.00
Undecanes	0.19	0.00	0.00	0.00	0.00	0.00	0.00
Dodecanes	0.08	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Gas Gravity	0.7555	0.7313	0.7273	0.7828	0.9415	1.1352	1.7094
Z-Factor	0.636	0.706	0.790	0.888	0.953	0.977	0.997

Figure 2. Oil Formation Volume Factors from Differential Vaporization Test

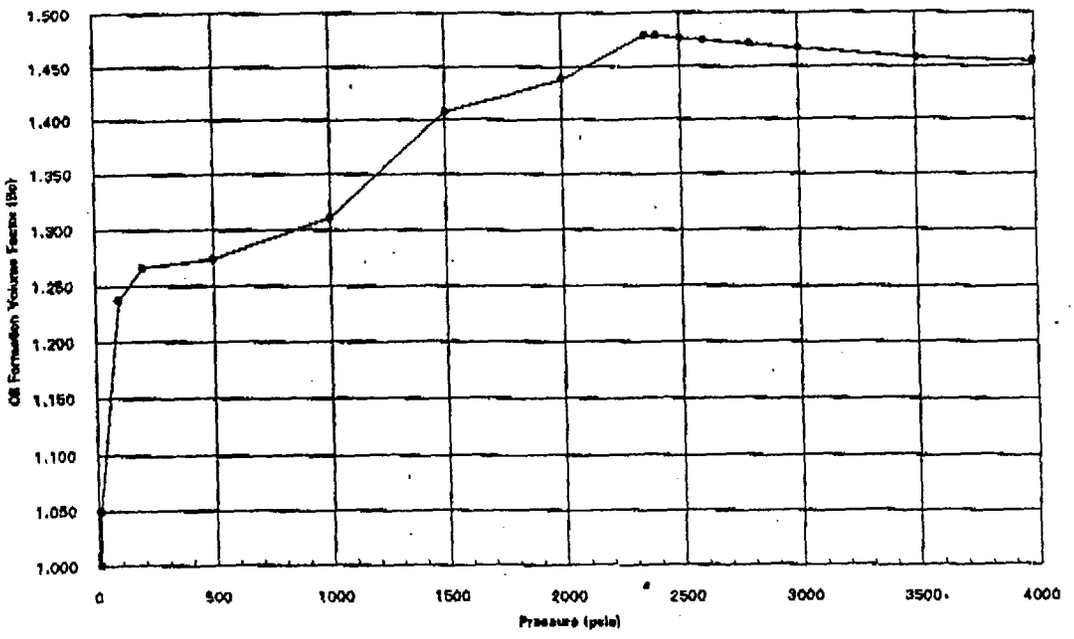


Figure 3. Solution Gas-Oil Ratios from Differential Vaporization Test

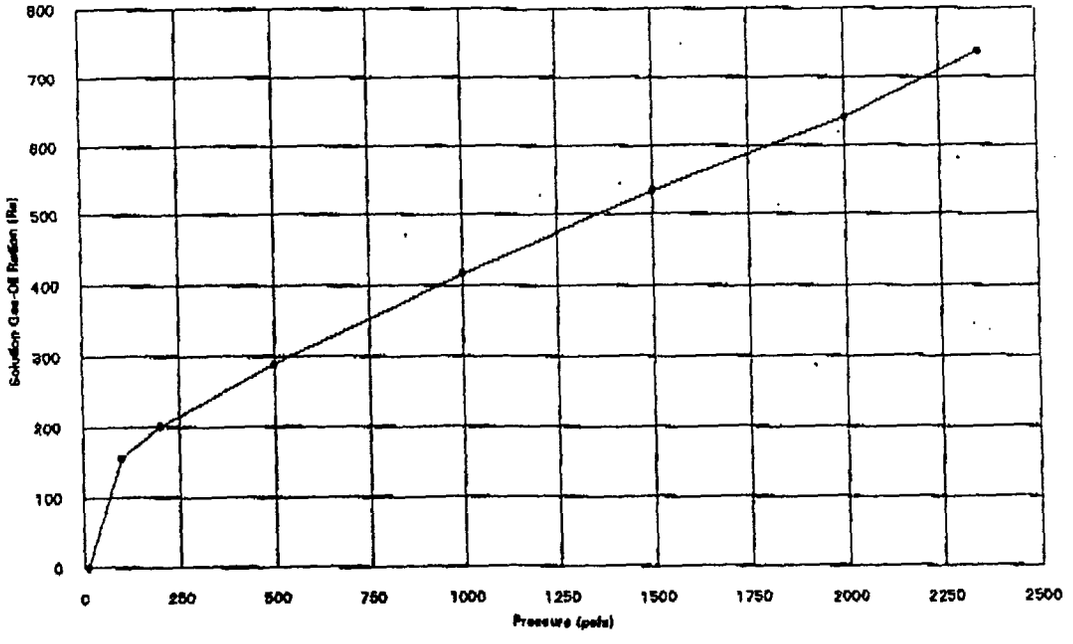
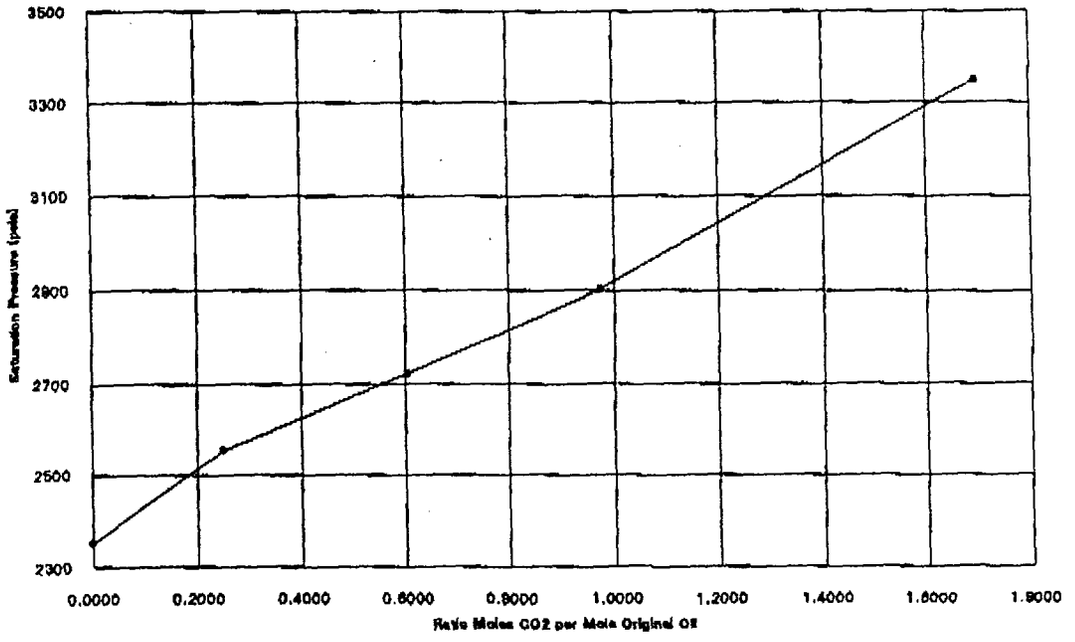


Table 9. CO2 Swelling and Viscosity Tests

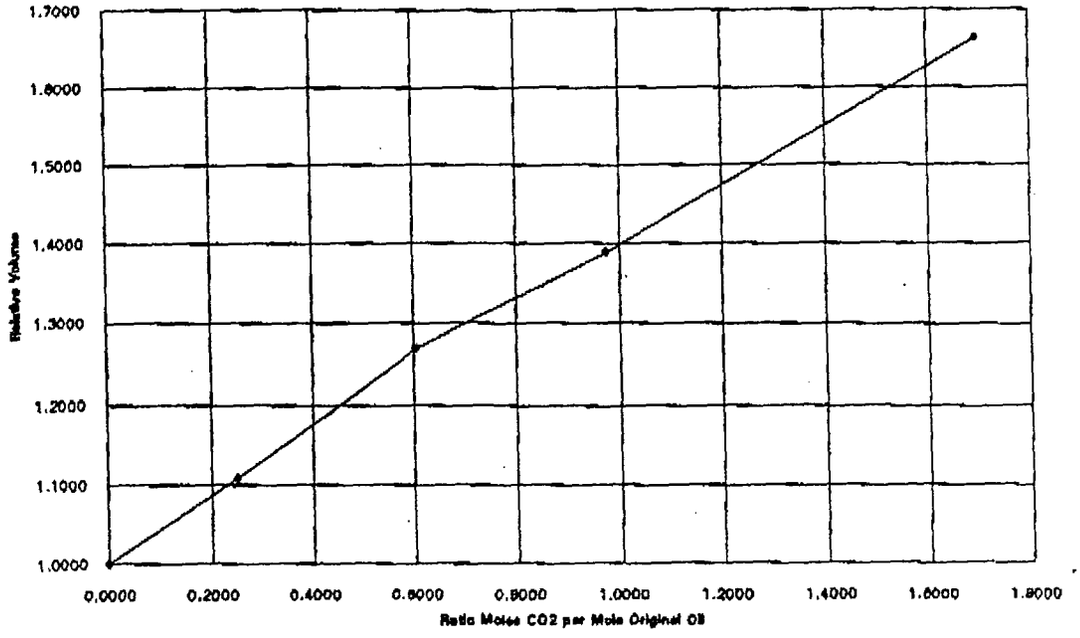
Percent CO_2 of total mixture	Ratio Moles CO_2 per Mole Oil	Saturation Pressure (psia)	Relative Volume[1]	Density at Saturation Pressure (g/cm^3)	Viscosity (cP)	Pressure for Viscosity Measurement (psia)
0.0%	0.0000	2352	1.0000	0.7271	0.434	2450
20.0%	0.2501	2554	1.1073	0.7362	0.355	2650
37.7%	0.6052	2724	1.2684	0.7414	0.283	2830
49.3%	0.9742	2902	1.3880	0.7713	0.240	3000
62.9%	1.6962	3350	1.6831	0.7967	0.222	3450

Figures 4. Saturation Pressures for Oil-CO2 Mixtures



[1]Total volume of the fluid (oil and CO_2) at the indicated pressure per volume of the original saturated oil at the bubble point pressure.

Figures 5. Relative Volume of Oil-CO2 Mixtures



Figures 6. Viscosities for Oil-CO2 Mixtures

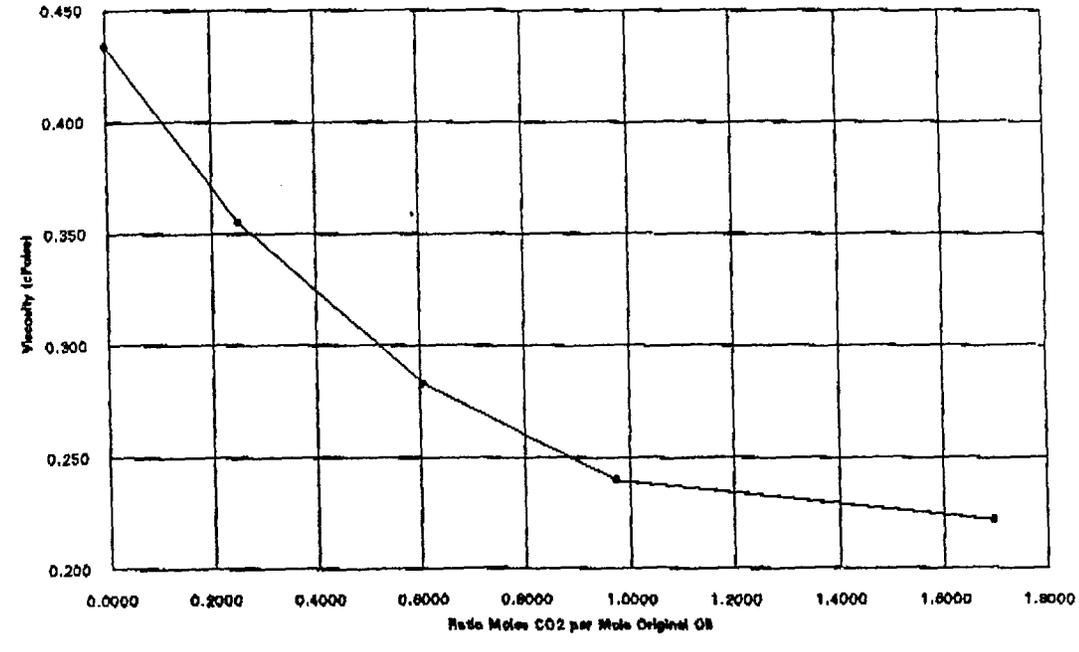


Table 10. Minimum Miscibility Pressure Tests

DV Pressure of Oil (psia)	MMP with CO2 (psia)
2354 *Original Oil*	2762
2000	2612
1800	2212
1500	1862
1000	1792
28 *Separator Oil*	1532
12	1462

Table 11. Separator Test

Pressure	43 psia
Temperature	65 °F
Liquid Relative Volume	1.68%
Gas-Oil Ratio (scf/bbl)	
Gas Composition (Mole Percent)	
Gas Composition (Mass Percent)	
Gas Gravity	
Gas Z-Factor	