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## Prediction of Liquid Hydrocarbon Recovery From a Gas Condensate Reservoir

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### ABSTRACT

A compositional model consisting of material balance (M-B) equations and the Peng-Robinson (P-R) Equation of State (EOS), was developed starting with the work of Bergman, Tek, and Katz. The model simulates constant volume expansion (CVE) as obtained from experimental analyses of gas condensates.

The contributions of this paper include the following: (1) evaluation of the phase behavior and fluid properties for an arbitrary mixture of components (2) development of the material balance equations to compute depletion performance, (3) investigation of P-R EOS as a tool for reproducing measured PVT data, and (4) analysis of the effect of component property estimation on EOS predictions.

The North Field Khuff reservoir, which is situated offshore northwest of the northern top of Qatar, and the specific K-4 reservoir description was used as the example in this work.

Laboratory measurements for constant volume depletion and phase separations of a condensate fluid sample were obtained from well No. NWD 5 in the K-4 reservoir of the North Field in Qatar. This experimental data was used as a basis for comparing results from the proposed compositional model. The data analysis was carried out up to C<sub>20+</sub> group hydrocarbons.

The experimental data used for comparison with the calculated results were volume percent liquid (retrograde condensation), cumulative produced volume, molecular weight of heavy components (C<sub>7+</sub>) produced, and compressibility factor. In addition to the values calculated above constant composition expansion at different temperatures, a partial phase diagram for K-4 gas condensate, and viscosity were calculated by the model.

### INTRODUCTION

Equations of State (EOS) have been used in recent years in compositional reservoir simulation.

References and illustrations at end of paper.

Compositional reservoir simulation is the process of inferring the behavior of the real reservoir from the model performance of that reservoir using the composition of the fluids recovered and that in place. It usually considers up to 30 components in any one, two, or three space dimensions. The purpose of an EOS is to determine K-values and equilibrium phase properties. It is most important in compositional reservoir simulation to get satisfactory agreement between EOS results and measured laboratory PVT data relevant to the fluid of the reservoir and its recovery process.

A number of studies emphasizing comparison of EOS and laboratory PVT results for a variety of reservoir fluids and conditions have been reported (1, 2, 3).

The North Field Khuff reservoir, which is situated offshore northwest of the northern top of Qatar as shown in Figure 1, is used as the example in this work. The discovery well was drilled in 1971. Subsequent wells confirmed that the North Field is a large gas condensate bearing structure occupying an area of approximately 1950 square miles. The producing carbonate reservoirs are subdivided into major subzones of the Khuff called (starting from the top) the K-1, K-2, K-3 and K-4. It is estimated the gas in place in the K-4 reservoir alone is about 125TCF. The fluid analysis of the K-4 interval has been completed and such analyses are extensively used in the reservoir predictions of this study (4,5). The field is as yet undeveloped.

Condensate gas fluid samples of Khuff reservoirs were obtained by recombining in surface separator gas and liquid products according to the producing liquid-gas ratio. Prior to recombination, both compositions of separator gas and separator liquid are obtained.

A recombined sample of reservoir fluid is placed in a pressure, volume, temperature (i.e. PVT) cell at a pressure above the dew point of 5120 psig and at the reservoir temperature of 220°F. The cell is expanded, thereby lowering the pressure. The mixture

is allowed to reach equilibrium. Then the vapor phase material is displaced at constant pressure while simultaneously withdrawing an equivalent volume of vapor until the cell volume is returned to the initial volume. The procedure is then repeated. At each step withdrawn vapor is analyzed using gas chromatography to determine compositions. Produced moles of vapor are calculated using real gas law and are reported as a cumulative percent of initial moles. Compressibility factor is also calculated observing produced vapor surface volume and equivalent cell volume at cell temperature and pressure. Then heptane plus (C<sub>7+</sub>) molecular weight is calculated from measured gravity and composition. Liquid volume is measured visually and reported as a percent of cell volume. The produced well stream viscosity is either measured or obtained by calculation.

This procedure is not true constant volume depletion but is a series of flashes to a predetermined pressure followed by vapor production at constant pressure.

The equation of state (EOS) material balance was developed and used to predict liquid that condenses out and recovery from laboratory constant volume expansion (CVE) experiments using K-4 reservoir fluid samples. These constant volume expansion (CVE) experiments are assumed to be representative of the primary depletion and retrograde condensation behavior of a gas condensate reservoir. The calibration of an EOS to match this data is critically important in order to predict liquid recovery using a reservoir simulator.

The Peng-Robinson (POR) equation of state and corresponding densities is used in preference over the Dykstra-Mueller (D-M) equation of state. The D-M method can suffer consistency problems between densities and phase behavior in the vicinity of the critical point. The P-R method, however, has the ability to force consistency between phase behavior and densities by adjusting K-values in an iterative convergence using fugacities. This method results in an additional simulation cost, but it is absolutely required for some problems.

#### THEORY

A simplified chart of the multi-component reservoir material balance computer program for the material balance constant volume expansion (M-B CVE) and Peng-Robinson equation of state (P-R EOS) model is shown in Figure 2. The fortran listing for the simulation package is presented in Appendix C of Reference (6). This program is an enhanced and modified version of the code presented by Bergman, Tek and Katz (7).

This program computes phase behavior and fluid properties for an arbitrary mixture of components. The program also has a heavy fraction (crude/condensate) characterization capability. The program will flash, perform constant volume expansion (Depletion) studies or gas injection/revaporization studies.

The program has the following features:

- Peng-Robinson equation of state
- Lorenz-Bray-Clark viscosities
- Heavy (pseudo) component characterization capability

- Fill PVT Table versus (P,T).

The program has the following subroutines:

- PVTIN = Case input and echo print
- HYPIN = Heavy pseudo component definition
- SRKIN = Loads default component properties
- PVTC = Computes flash and properties
- PHASE = Computes flash at reservoir pressures and temperatures
- FLASH = Computes vapor/liquid equilibrium
- FUGCTY = Computes fugacity of a phase
- RULMIX = Computes new A and B parameters for E-O-S
- VOLMPR = Computes specific volume by Peng-Robinson E-O-S
- CUBEQ = Computes roots of cubic equation
- PROP = Computes fluid properties
- OUTP = Prints computed properties
- VISC = Computes phase viscosity
- TABLE = Prints table of values versus (P,T)
- TITLE = Prints heading and title

#### COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS

Experimental observed results of constant volume expansion have been compared with the calculated results determined by M-B and P-R EOS after adjustment of heavy fraction critical properties such as critical temperature critical pressure and acentric factor. These adjustments have reduced the maximum difference between the predicted and measured.

Figure 3 shows the liquid retrograde condensation as a function of pressure for both the laboratory experiment and the material balance composition model. The calculation was carried out to 566 psia starting from initial reservoir pressure at 5300 psia. Retrograde liquid began to drop out at the dew point pressure at 5135 psia. The liquid drop out increases with pressure reduction and reaches a maximum of 2.4 percent at about 1800 psia. At pressure of 1500 psia the retrograde condensation starts to revaporize which causes the volume percent liquid to decrease from about 2.4 percent down to 2.1 percent at 565 psia. The above comparison shows very good agreement between the experiment and the model results up to the maximum liquid dropout pressure at 1800 psia which is more important than lower pressure condition since reservoir may not be produced at lower pressure.

Figure 4 and Table 1 show the comparison of computed and measured produced volume in the depletion experiment. There is a slight difference at intermediate pressure between computed and observed. This difference could have occurred due to misreading the small measured volume during the process of the experiment.

Figure 5 shows the measured and calculated molecular weight (MW) of heavy components (C<sub>7+</sub>). A maximum difference of about 4 percent has been found between predicted and measured MW. Higher produced MW's indicate less mass remaining in the reservoir. Adjustment of the heavy component molecular weight (C<sub>7+</sub>) to match the above measured retrograde liquid is attributed to the observed difference using the correlation to compute the MW of heavy components.

Comparisons between the compressibility factor (Z) of the experiment and that calculated by the model are shown in Figure 6. The maximum difference was estimated to be 2.4 percent. The model predicted lower compressibility factor than the measured value

which indicates more mass is produced in the Model Case. The above difference in molecular weight, produced volume and retrograde liquid caused the difference in the measured and calculated compressibility factor.

Figure 7 shows the comparison of computed and reported viscosity by different correlations. Produced fluid viscosity, as computed by the model, shows reasonable agreement with the viscosity shown in the laboratory report. These two viscosities were calculated by different correlations. Viscosity in the PVT report was calculated with equations from Standing (Behavior of Oil Field Hydrocarbon System) while the Lohrenz, Bray, and Clark correlation for viscosity was used in the model. The maximum difference between these correlations show about 4 percent.

Viscosity calculated by the model will be used in the production performance of the reservoir since it is more consistent with the other calculated parameters.

Table 2 shows comparison of the laboratory measured equilibrium gas composition with those calculated using M-B and P-R EOS compositional model at pressures of 4759 and 3244 psia. From this table it can be seen that at a pressure of 3244 psia, the produced mole fraction of heavy component ( $C_{7+}$ ) is lower than the produced mole fraction of  $C_{7+}$  at 4759 psia which results from higher liquid dropout due to pressure decline below dew point pressure. Produced light components such methane ( $C_1$ ) behave opposite the heavy component as shown in Table 2.

#### Phase Diagram

Figure 8 shows the variation of liquid volume with pressure for the initial reservoir composition. A partial phase diagram is obtained by cross plotting the curves of Figure 8 as presented in Figure 9. For example, enter Figure 8 at a specified volume percent liquid. Move horizontally to the right until you hit the first curve, read temperature and pressure of that curve, then move to the next curve and take a reading. This process is continued until you get all points resulting from the intersection of liquid volume fraction with the curves. From these points one curve for the phase diagram can be constructed at one volume percent liquid value.

From the behavior of the quality lines of Figure 9 the critical temperature of the system is believed to be considerably less than 0°F.

#### Heptane-Plus Characterization

The results of this study indicate that predictions of an EOS are highly sensitive to characterization of the heptane-plus ( $C_{7+}$ ) fraction.

Reservoir depletion calculations for gas condensates by the model have been used for  $C_{7+}$  as one pseudo component and with the  $C_{7+}$  split into fourteen fractions ending with the same molecular weight. Critical properties of extended heptane-plus ( $C_{7+}$ ) up to fourteen components were adjusted. These adjustments improved the calculated results as compared with measured.

Figure 10 shows comparison of retrograde liquid condensation for calculated and measured results. Three different results were obtained by the model for different cases. Case one shows the predicted behavior of liquid dropout during depletion for one pseudo component ( $C_{7+}$ ). The second case shows the predicted performance of retrograde liquid condensation with heptane-plus ( $C_{7+}$ ) split into fourteen fraction without making any adjustment for EOS parameters. The third case shows the behavior of retrograde liquid condensation during the depletion processes after the adjustment of EOS parameters.

#### Adjusted EOS Parameters

After several runs of the EOS model it was observed that there is a characteristic influence of heptane-plus on the predictions of equation of state (EOS). Several observations were made on the effect of the adjustment of extended analysis of heavy components ( $C_{7+}$ ). The adjustment of  $C_{7+}$  properties plays an important role in matching constant volume depletion experiment results such as retrograde liquid condensation, produced vapor composition, produced vapor volume compressibility factor of produced and in place fluid, vapor viscosity and density.

The critical properties adjustment of the extended analysis of heavy components ( $C_{7+}$ ) are presented graphically in Figures 11 through 13 for gas condensate. Figure 11 shows the effect of critical temperature ( $T_c$ ) on retrograde condensation and saturation pressure. A decrease in  $T_c$  for heavy components ( $C_7 - C_{20+}$ ) by 10 percent results in a reduction in maximum retrograde condensation and an increase in pressure saturation. A decrease in  $T_c$  for  $C_7 - C_{10}$  components results in a decrease in both saturation pressure and retrograde liquid. It has more influence on liquid dropout at lower pressure. Decreasing  $T_c$  of the intermediate heavy components ( $C_{11} - C_{17}$ ) causes a reduction in maximum retrograde liquid. A decrease in  $T_c$  of components  $C_{18} - C_{20+}$  results in an increase in saturation pressure.

The effect of critical pressure ( $P_c$ ) of the extended analysis on liquid dropout and saturation pressure has also been studied, as shown in Figure 12. From these adjustments it has been shown that increasing  $P_c$  of heavy components ( $C_7 - C_{20+}$ ) the saturation pressure is increased and maximum liquid dropout is reduced. Increase in  $P_c$  for  $C_7 - C_{10}$  components results in an increase in saturation pressure and a decrease in retrograde liquid condensation. An increase in critical pressure for  $C_{11} - C_{17}$  component causes an increase in saturation pressure with little effect on maximum liquid dropout. An increase in critical pressure for  $C_{18} - C_{20+}$  components results in an increase in saturation pressure with no significant reduction in maximum liquid dropout.

Acentric factor has an effect on both saturation pressure and liquid dropout. Increasing acentric factor of  $C_7 - C_{10}$ ,  $C_{11} - C_{17}$  or  $C_{18} - C_{20+}$  increased both maximum liquid dropout and saturation pressure. Sensitivity effect of acentric factor is shown in Figure 13.

From the above analysis it was shown that the effect of heptane-plus (C7+) characterization on predictions of the EOS model is substantial for reservoir fluid. Satisfactory predictions of PVT properties can only be achieved by adjusting the critical properties of components.

### CONCLUSIONS

A mathematical simulation procedure for the prediction of primary depletion of gas condensate reservoirs has been developed. Based on the work done in this research the following conclusions can be drawn.

1. One of the most powerful methods for predicting reservoir fluid behavior at conditions other than those measured is the equation of state (EOS).
2. K-values derived from the equation of state (EOS) material balance model, developed in this work, can be correlated to estimate apparent convergence pressure and characterization factor of heavy components.
3. Results indicate that the predictions of an equation of state are very sensitive to characterization of the heptane-plus fraction.
4. A procedure has been devised to adjust the equation of state parameters, otherwise it will overestimate the dropout liquid volume versus pressure in a gas condensate reservoir. Guidelines are developed and provided for adjusting equation of state parameters such as  $T_c$ ,  $P_c$ ,  $W$ , and  $MW$  to achieve satisfactory prediction of retrograde liquid and vapor phase behavior.
5. The studies done with the EOS and material balance model indicate that the splitting of C7+ into multiple pseudo components is necessary and sufficient to match PVT data.
6. Reservoir fluid property data for many samples needs to be matched with an EOS before complete confidence in reservoir simulator predictions can be achieved.

### NOMENCLATURE

- $f_l$  = Pure component fugacity of liquid  
 $f_v$  = Pure component fugacity of vapor  
 $K$  = Equilibrium constant in vapor-liquid system  
 $MW$  = Molecular weight  
 $MW_v$  = Molecular weight of vapor  
 $P_c$  = Critical pressure  
 $T_c$  = Critical temperature  
 $V$  = Total number of moles in vapor  
 $W$  = Accentric factor

- $X_i$  = Mole fraction of ith component in liquid phase  
 $Y_i$  = Mole fraction of ith component in vapor phase  
 $\lambda_{PR}$  = Peng-Robinson calculated retrograde condensation fraction  
 $\mu_l$  = Viscosity of liquid  
 $\mu_v$  = Viscosity of vapor  
 $\rho_l$  = Density of liquid  
 $\rho_v$  = Density of vapor

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TABLE 1  
COMPARISON OF COMPUTED AND MEASURED  
RETROGRADE LIQUID AND CUMULATIVE PRODUCED

Pressure psig	Retrograde Liquid Deposit (%)		Cumulative Produced Volume (%)	
	Measured	Computed	Measured	Computed
5120	0.00	0.00	0.00	0.00
4759	0.14	0.14	4.54	5.10
4426	0.37	0.36	8.95	10.00
2051	0.82	0.78	14.62	16.00
3678	1.24	1.20	24.44	22.06
3244	1.79	1.72	28.14	30.10
2737	2.15	2.10	38.26	40.00
2314	2.31	2.30	47.52	49.07
1905	2.40	2.42	56.76	58.40
1468	2.37	2.40	66.87	68.03
968	2.21	2.30	78.31	78.90
550	2.02	2.15	87.53	87.79

TABLE 2  
COMPARISON OF LABORATORY EQUILIBRIUM VAPOR  
COMPOSITION WITH COMPOSITION DETERMINED BY  
M-B AND P-R MODEL AT 4759 PSIA & 3244 PSIA

Component	Mole Percent @ 4759 psia		Mole Percent @ 3244 psia	
	Measured	Computed	Measured	Computed
H <sub>2</sub> S	0.53	0.53	0.53	0.53
CO <sub>2</sub>	1.76	1.78	1.76	1.78
N <sub>2</sub>	3.36	3.38	3.22	3.40
C <sub>1</sub>	83.51	83.00	84.94	84.24
C <sub>2</sub>	5.17	5.28	5.12	5.20
C <sub>3</sub>	1.91	1.95	1.84	1.94
I-C <sub>4</sub>	0.41	0.42	0.36	0.41
n-C <sub>4</sub>	0.70	0.71	0.65	0.69
I-C <sub>5</sub>	0.28	0.29	0.26	0.28
n-C <sub>5</sub>	0.28	0.29	0.24	0.27
C <sub>6</sub>	0.39	0.41	0.31	0.37
C <sub>7+</sub>	1.70	1.96	0.77	0.89

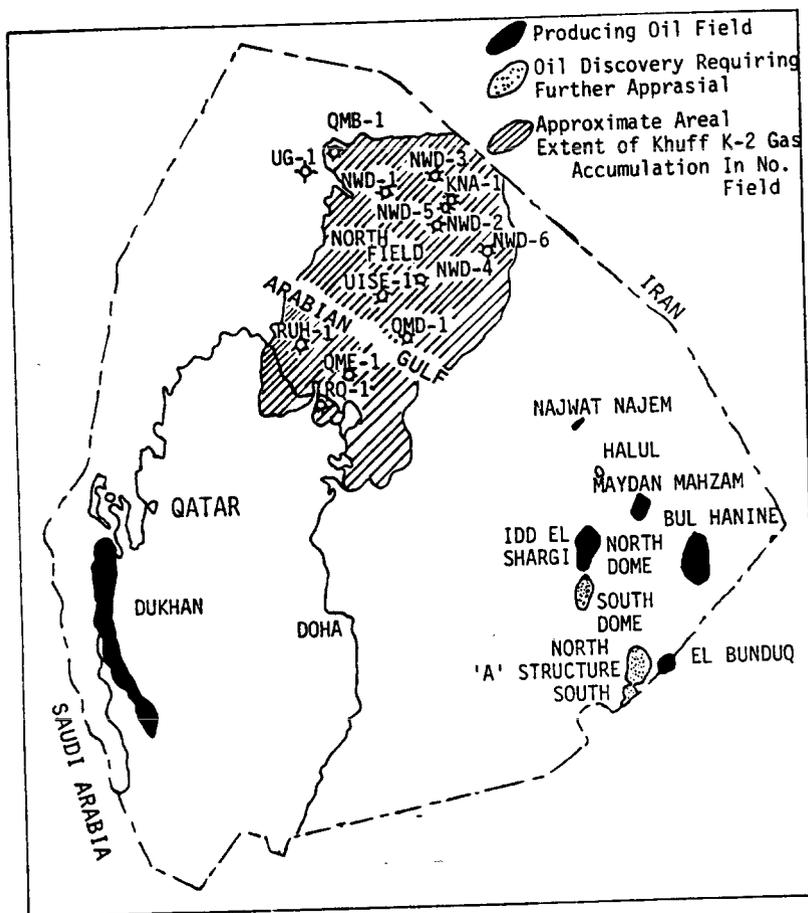


Fig. 1—Location map of North field.

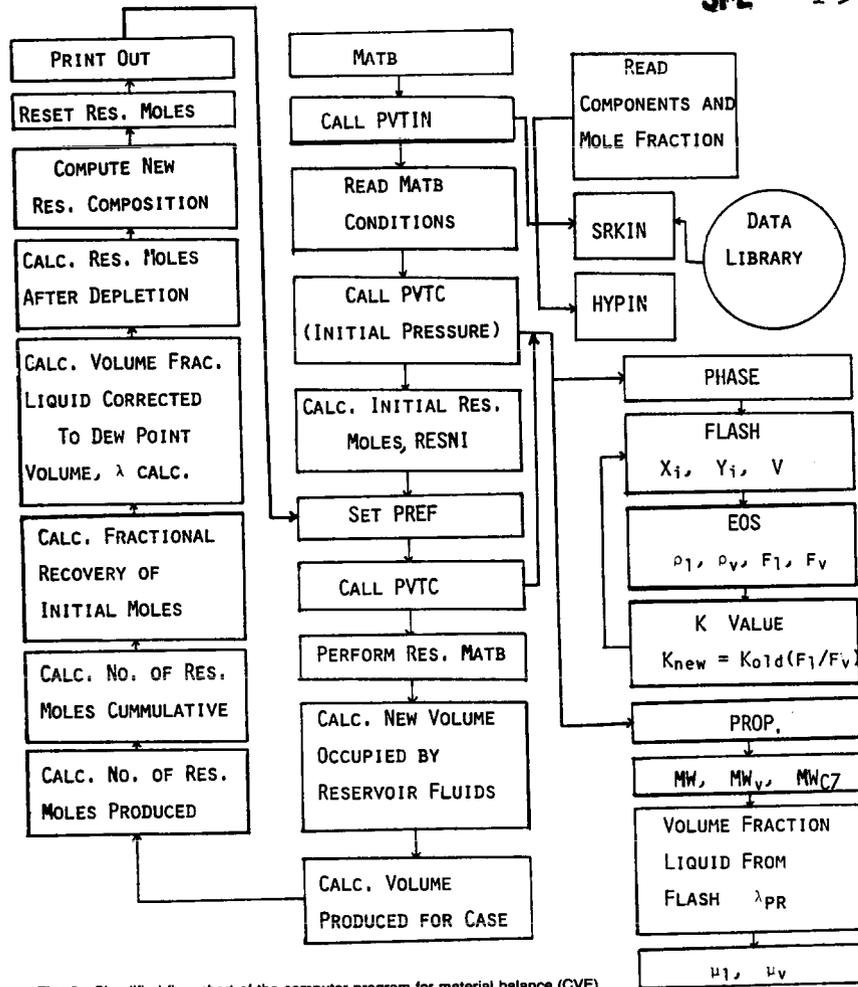


Fig. 2—Simplified flow chart of the computer program for material balance (CVE).

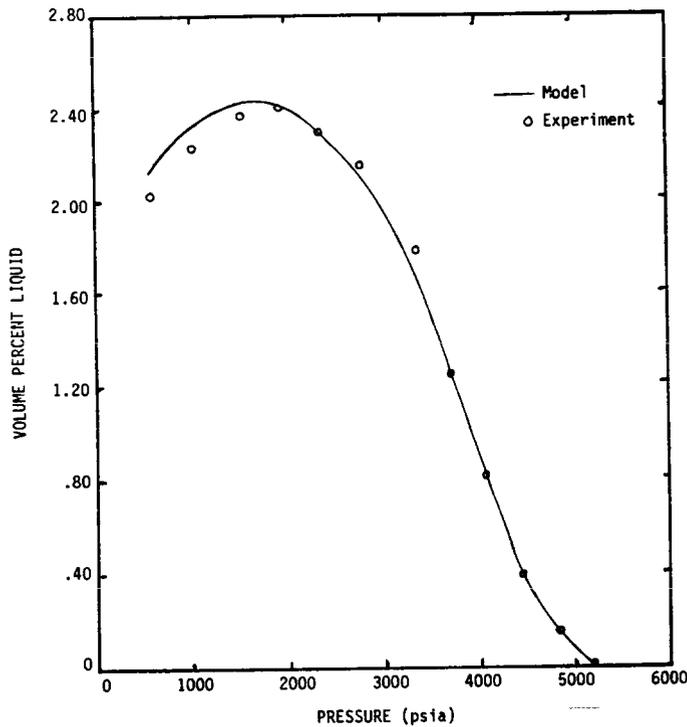


Fig. 3—Comparison of computed and measured volume percent liquid.

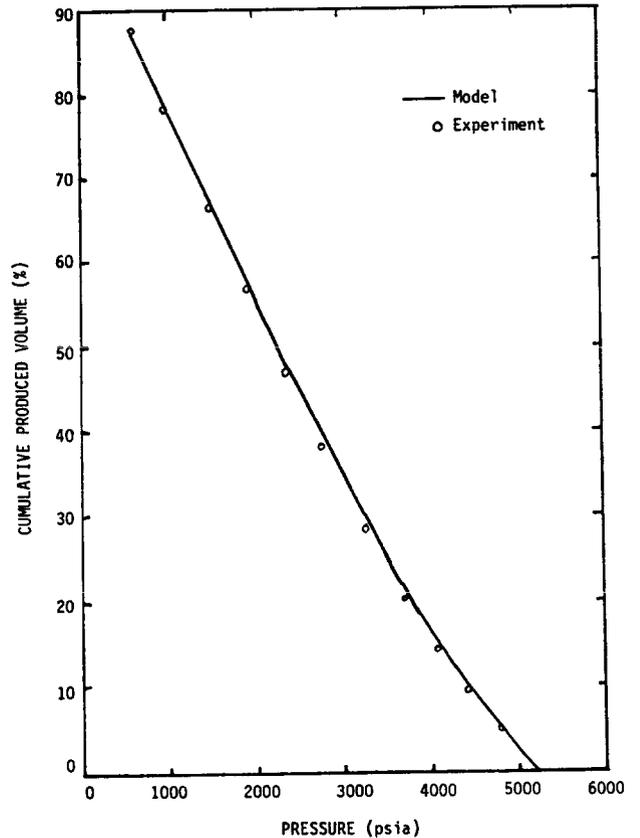


Fig. 4—Comparison of computed and measured produced volume.

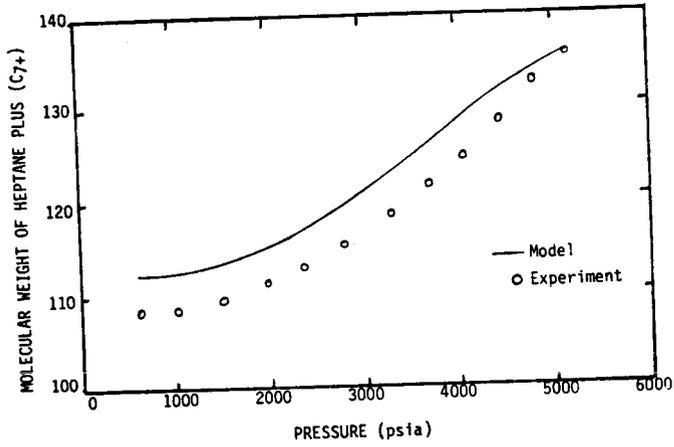


Fig. 5—Comparison of computed and measured molecular weight of heptane-plus.

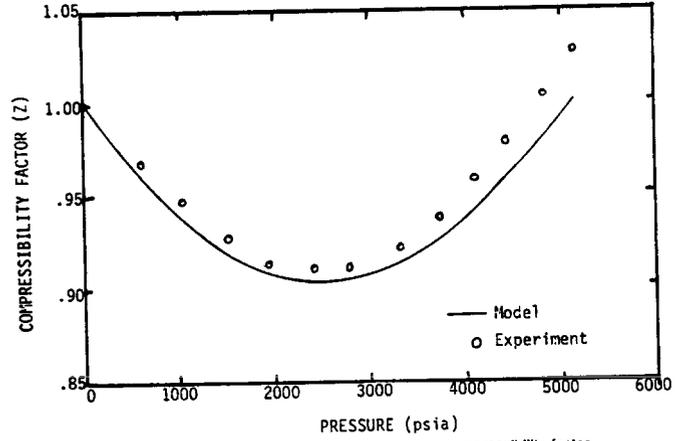


Fig. 6—Comparison of computed and measured compressibility factor.

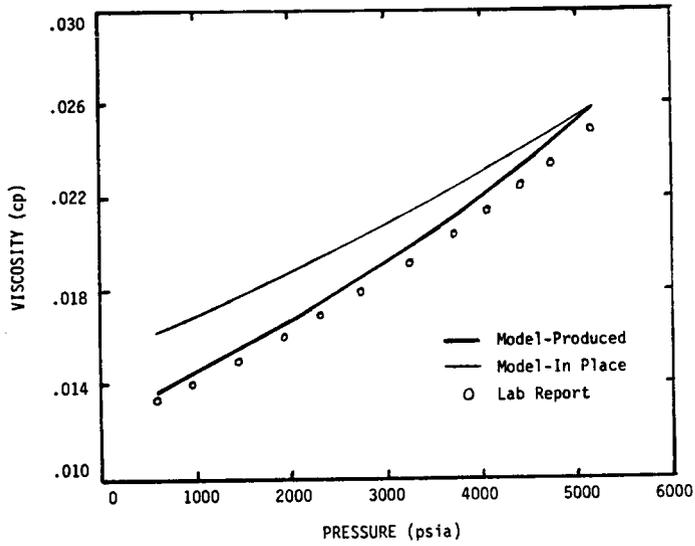


Fig. 7—Comparison of computed and reported viscosity.

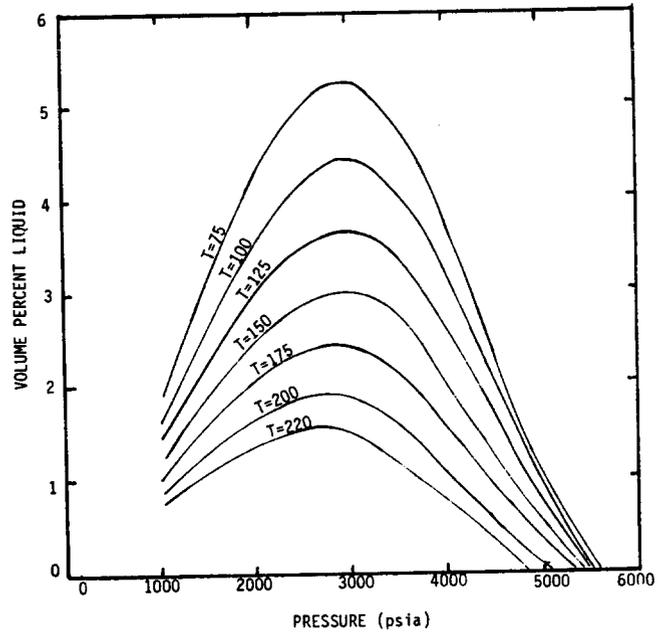


Fig. 8—Constant composition expansion at different temperatures.

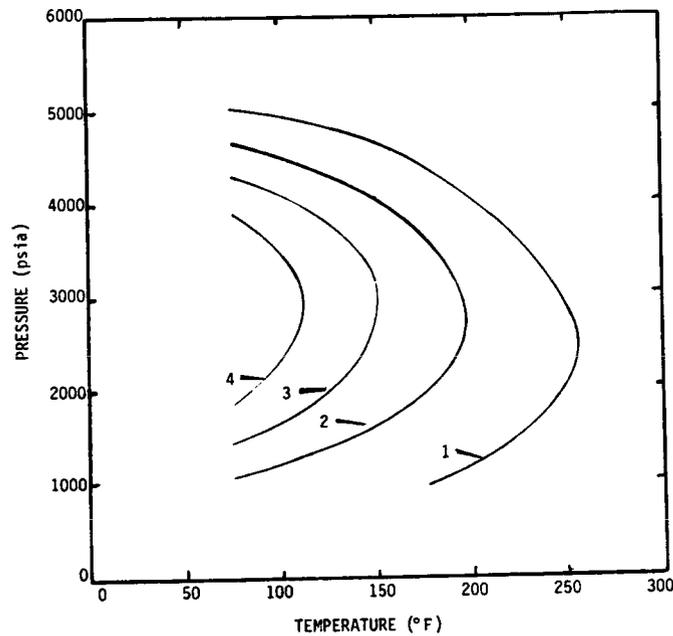


Fig. 9—Partial phase diagram for K-4 gas condensate reservoir.

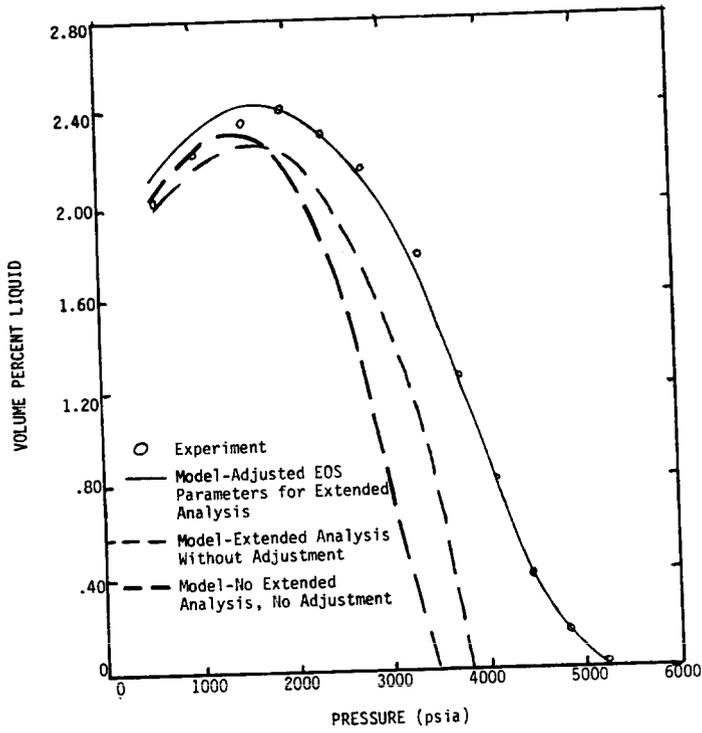


Fig. 10—Comparison of computed and measured volume percent liquid.

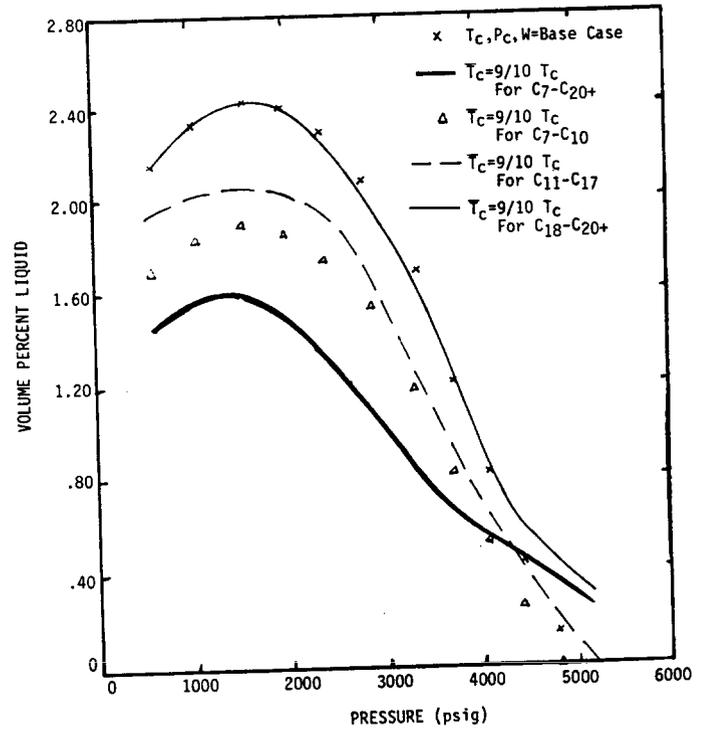


Fig. 11—Sensitivity effect of critical temperature on retrograde liquid condensation.

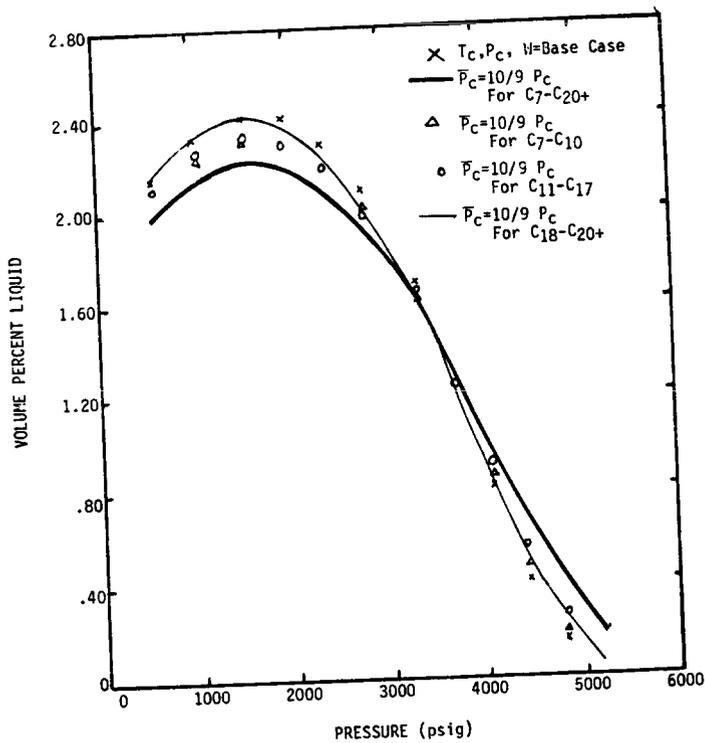


Fig. 12—Sensitivity effect of critical pressure on retrograde liquid condensation.

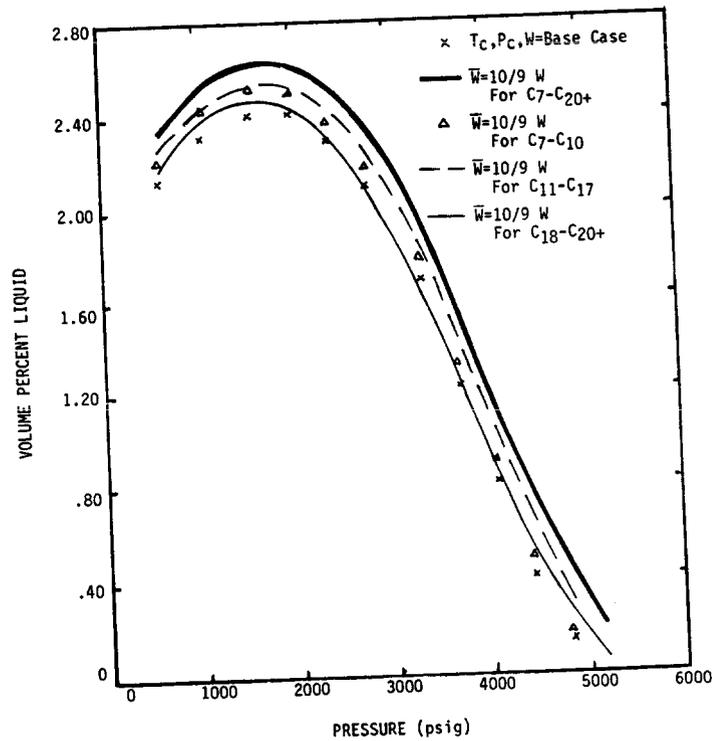


Fig. 13—Sensitivity effect of acentric factor on retrograde liquid condensation.