

# Deconvolution of Drilling Fluid-Contaminated Oil Samples

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## ABSTRACT

*Reservoirs can sometimes be very sensitive to drilling fluids. Typically, the lower the permeability of the rock, the greater the likelihood of experiencing phase interference effects; as the average diameter of the porous features decreases, the greater the capillary pressure. Many times this phase interference effect significantly reduces well productivity and hence, alternative drilling fluids are used. Moreover, aqueous phase fluids can react with the reservoir rock causing clay swelling, clay flocculation and fines migration.*

*In an attempt to mitigate the above-mentioned deleterious phenomena, alternative non-aqueous drilling muds are sometimes used. These are designed to be compatible with the reservoir fluids in-situ and because*

*they are hydrocarbon-based, they do not interact with the rock matrix. One of the drawbacks, however, is the mixing that occurs with the oil in-situ. When early-time samples are taken, the oil is contaminated with the drilling fluid. This is a near-wellbore and early-time problem that is self-correcting as more fluids are produced from the well. However, for small volume samples (typically bottom hole samples), contamination can seriously distort the properties measured on the sample. The small-volume samples are often very expensive to procure and many of the reservoir-development decisions are based on the properties of these small samples. The properties need to be accurately measured therefore.*

*How can the contamination be quantified both in terms of mass or mole percent in the fluid and its impact*

on the sample properties? This paper describes two technologies developed to achieve this. The first is applicable to synthetic hydrocarbon drilling fluids where the concentration of components is restricted to very few components. The second technique applies to those fluids that contain a more broad distribution of hydrocarbon components.

The results indicate that the resolution of contamination can be achieved to within 1 mass percent accuracy. Using the degree of contamination with Equation of State methods, can they predict properties of the reservoir fluid to within 4% of actual value?

## OBJECTIVE

The objective of this work is to develop a technique that will quantify how much contamination is present in the sampled oil and then provide a means by which PVT parameters on reservoir fluid can be approximated from a contaminated sample. The basis for this work is having no “clean” oil available and therefore the uncontaminated properties must be extrapolated from the available samples. The scope of the work consists of:

- Mathematical development
- Additional experimental data on selected samples
- Validation of mathematical approach
- Estimation of the oil-based mud filtrate contamination on selected samples

## METHODOLOGY

Depending on the type of drilling fluid, the determination of the amount of contamination can be facile or it may be somewhat more involved. From the authors’ experience, drilling fluids whose compositional distribution is very narrow are the easiest to correct. This type will be discussed in the first section. Those drilling fluids that possess a much broader distribution of components are more difficult to quantify. This type is discussed in Section 2.

### Type 1 – Narrow Range of Components

Figure 1 depicts what is intended by a narrow range of components in the contaminating drilling fluid. There is an obvious peak associated with C<sub>10</sub> to C<sub>15</sub>. The first step

is therefore to determine what fraction of the sample (some amount of reservoir fluid plus some amount of drilling fluid – both of which are unknown) is contaminated. Once the degree of contaminant is quantified, EOS techniques can be employed to “back out” the effect on the properties. How these steps are accomplished will be described next.

For the determination of contamination fraction, Figure 2 describes the common distribution observed for most reservoir fluids. By plotting the log number of moles versus carbon number, a good straight line relation is obtained. Extrapolating to infinite numbers provides the number of moles in the reservoir fluid. Comparing Figures 1 and 2, even if the only sample of reservoir fluid is contaminated, one can measure the number of moles of contaminant by chromatography.

Once the moles of sample are known, the following equations can be used to determine uncontaminated properties:

### Molecular Weight

$$MW_{\text{sample}} = \text{Mole Fraction}_{\text{oil}} MW_{\text{oil}} + (1 - \text{MF}_{\text{oil}}) MW_{\text{contaminant}} \quad (1)$$

where MF<sub>oil</sub> – Mole Fraction Oil

### Density

$$\rho_{\text{sample}} = \text{VF}_{\text{oil}} \rho_{\text{oil}} + (1 - \text{VF}_{\text{oil}}) \rho_{\text{contaminant}} \quad (2)$$

where VF<sub>oil</sub> – Mass Fraction<sub>i</sub> ρ<sub>total</sub>/ρ<sub>i</sub> according to ideal mixing.

Once the mole fraction, MW and density of the oil are determined then all the parameters are known for EOS modeling. So to review, by superposition:

1. Moles of oil and contaminant are determined.
2. Mass and volume fractions are calculated.
3. With these, the mole fractions of oil and contaminant, density of uncontaminated oil and the molecular weight of the uncontaminated oil are calculated.
4. The C<sub>6+</sub> characterization can then be done for the plus fraction of the oil. The contaminant can be characterized separately.

The procedure for correcting for contamination is therefore:

1. Two sets of hypothetical components are used: one for the oil C<sub>6+</sub> and one for the contaminant components.
2. Base grouped properties are based on oil properties.
3. Plus fraction properties are modified to match experiment data.

With this procedure, the effects of contamination can then be removed by:

1. Measurements are made on the contaminated sample.
2. The EOS is tuned to the experimental data with the two sets of hypothetical components.
3. Theoretically the contaminant is removed and the “uncontaminated” oil properties are provided.

Using this protocol, Figures 3 and 4 show the predictions of bubble point pressure and the error as a function of contamination level. Figures 5 to 7 provide the same comparison between predicted and experimental for Bo, GOR and density. The EOS predictions, in all cases, were based on an EOS tuned to the contaminated PVT data, measured experimentally, and then the contamination was “removed” in the EOS model. The experimental values, in the figures, were those measured on an uncontaminated sample.

## Type 2 – Broad Range of Components

Many times, a less refined hydrocarbon stream is used as the drilling fluid. In such cases, the determination of the degree of contamination is more challenging. Figure 8 shows four profiles: the reservoir fluid, as sampled, possibly containing some contaminants, the same sample spiked with 10 mass % and 50 mass%. There is a trend as contamination increases, but the difference is much more subtle than with a fluid where the component range is narrow. What follows is the development of a technique to remove the amount of contaminant.

## MATHEMATICAL DEVELOPMENT

At first the problem seems trivial. A simple statement of mass balance is

$$Z_i = AX_i^{\text{mud}} + (1-A)X_i^{\text{oil}} \quad (3)$$

where  $Z_i$  is the composition (mass fraction) of component  $i$ , in the sampled oil, as received from the

field.  $X_i^{\text{mud}}$  is the mass fraction of component  $i$  in the mud (also known). However,  $A$  and  $X_i^{\text{oil}}$  are unknown and are the mass fraction of the drilling fluid, or mud, in the oil sampled and  $X_i^{\text{oil}}$  is the amount of the component in the “clean” oil, which is unknown.

$A$  can be generally defined as

$$\frac{\text{Mud}}{\text{Mud} + \text{Oil}}$$

and this is the objective of the development.

Using Equation (3), two unknowns and one equation, we have a non-unique solution and, in fact, many solutions. Another equation was therefore sought.

A physical procedure was used to “spike” the sample with a known quantity of drilling fluid, or mud. The same relationship can be used with the spiked sample, as Equation (3)

$$Z_i^{\text{spike}} = BX_i^{\text{mud}} + (1-B)X_i^{\text{oil}} \quad (4)$$

$$B \text{ is now } \frac{\text{Mud} + \text{Spike Mass}}{\text{Mud} + \text{Oil} + \text{Spike Mass}}$$

$A$  and  $B$  can therefore be expressed as

$$A = \alpha_1 \text{Mud} + \beta_1$$

$$B = \alpha_2 \text{Mud} + \beta_2$$

To test the applicability of this approach, two samples were prepared: one with approximately 10% mud addition and another with approximately 50% mud added.

The actual numbers were:

1. 0.7739 g of sampled oil  
0.0867 g of mud
2. 0.6480 g of sampled oil  
0.6688 of mud

Therefore,

$$A = \alpha_1 \text{Mud} + \beta_1 = \frac{\text{Mud} + 0.0867}{0.7739 + 0.0867}$$

$$\alpha_1 = 1.16198$$

$$\beta_1 = 0.10074$$

For the second addition:

$$B = \alpha_2 \text{Mud} + \beta_2 = \frac{\text{Mud} \left( \frac{.6480}{.7739} \right) + .6688}{.6480 + .6688}$$

$$\alpha_2 = 0.63587 \quad \beta_2 = 0.50789$$

The 0.648/0.7739 factor is used so that A and B can be related through one variable, mud.

Equation (4) can then be assembled for every component

i

$$Z_i^{S1} = (\alpha_1 \text{Mud} + \beta_1) X_i^{\text{Mud}} + (1 - \alpha_1 \text{Mud} - \beta_1) X_i^{\text{Oil}}$$

$$Z_i^{S2} = (\alpha_2 \text{Mud} + \beta_2) X_i^{\text{Mud}} + (1 - \alpha_2 \text{Mud} - \beta_2) X_i^{\text{Oil}}$$

Put into matrix form, we have

$$\begin{bmatrix} \alpha_1 (X_i^{\text{Mud}} - X_i^{\text{Oil}}) & (1 - \beta_1) \\ \beta_2 (X_i^{\text{Mud}} - X_i^{\text{Oil}}) & (1 - \beta_2) \end{bmatrix} \begin{Bmatrix} \text{Mud} \\ X_i^{\text{Oil}} \end{Bmatrix} = \begin{Bmatrix} Z_i^{S1} - \beta_1 X_i^{\text{Mud}} \\ Z_i^{S2} - \beta_2 X_i^{\text{Mud}} \end{Bmatrix}$$

Analyzing the integrity of the equations by computing the rank of the coefficient matrix:

$$\alpha_1 (X_i^{\text{Mud}} - X_i^{\text{Oil}}) (1 - \beta_2) - \alpha_2 (X_i^{\text{Mud}} - X_i^{\text{Oil}}) (1 - \beta_1)$$

or

$$\alpha_1 (1 - \beta_2) - \alpha_2 (1 - \beta_1)$$

Substituting the values for  $\alpha_1, \alpha_2$  and  $\beta_1, \beta_2$ :

$$1.16198 (1 - .50789) - 0.63587 (1 - .10074) = 0$$

Consequently, the determinant is zero and therefore the equations are not independent. There would be infinite solutions or at least multiple solutions. Another independent relation is required. Another approach was therefore investigated.

### Objective Function Minimization Approach

Studying the mass fraction versus carbon number relationship, there is a very good log linear functionality. Figure 8 shows this for the subject sample. Of increased importance is the correlation of the slope and Y intercept

of these same mass fraction functions. Figure 9 provides the Y intercept and the slope of these data as a function of mud filtrate mass fraction. The assumed mud filtrate fraction determines the location of the three points along the x-axis (the 100% filtrate fraction does not change in location). Extrapolation back to zero provides a best fit log linear approximation of uncontaminated oil. The X axis is defined as:

$$X = \frac{\text{Mud} + \text{SpikedMud}}{\text{Mud} + \text{Oil} + \text{SpikedMud}} \quad (5)$$

Due to the non-linear nature of the equations, the algorithm is as follows:

1. Assume mud filtrate fraction (MF).
2. Compute mass of MF in oil.
3. Calculate X corresponding to the two spiked samples (Equation 3).
4. Regress on the values of Y intercept and slope of Figure 8.
5. Calculate mass fraction of component i in uncontaminated oil based on extrapolated intercept and slope at the zero contamination condition\*.
6. Use Equation 4 to compute  $X_i^{\text{Oil}}$  for each component equation based on MF assumed initially.
7. Iterate on MF until a minimum error between step 5 and step 6 summed over components 13-29 is achieved.

\* This is part of the iteration. This should not be construed to be the final answer but is part of the iteration process, wherein an update of the oil composition is achieved.

The objective function versus contamination level for the sample is shown in Figure 10. This analysis indicated that the sample, as received, had 4.8 mass % mud filtrate contamination.

### Validation of Mathematical Approach

Since this approach is numerical and relies upon minimization of a residual sum of squares, two test cases were performed so that the algorithm could be ratified. The results ensue.

A “blind” test was performed by choosing a separate cylinder to which a specific quantity of mud filtrate was added. This “contaminated” sample was then used as the base oil. Two “spikes” were then performed by adding specific masses of mud filtrate to known masses of the base oil (oil plus the unknown quantity of mud filtrate). The objective was to use the above-described approach and to compute the amount of the mud filtrate used to contaminate the oil from the second cylinder.

The algorithm was used and the objective function from step 7 (from the above algorithm) was minimized. Figure 11 shows the result. The mass of mud filtrate that was added to the oil was 0.6802 grams and the oil mass was 2.6438 grams, or a mass fraction contamination of 0.2046. From the above algorithm a value of 0.21 was computed. The error was approximately 0.50 mass %. Figure 12 shows the y intercept and the slope relationship as a function of contaminated fraction. They are very linear and therefore the extrapolation to the zero contamination condition should be trustworthy. The result in Figure 11 confirms this even at 20.5 mass % contamination. Table 1 shows the compositions of the corrected oil and the actual oil. Working from the 20% contaminated base line, the corrected oil compares closely with the actual. Figure 13 shows the same data along with the errors involved. (In light of the intrinsic errors of the chromatograph for values less than 1 mass %, the absolute errors are reported, instead of percentage errors, for those specific components.)

Another blind contamination test was then performed. This time, a separate cylinder (#3) was contaminated with mud filtrate: 3.7917 grams of oil and 0.4401 grams of mud filtrate (filtrate mass fraction contamination of 0.1040). The above algorithm was used again and the result is shown in Figure 14. A value of 9.6 mass % contamination was computed compared to the value of 10.4 mass %. Table 2 presents a comparison of the corrected and actual oil compositions. It is therefore proposed that this algorithm will yield contamination accuracies to within 1 mass % of the actual value. Figures 15 and 16 show the results as in the previous application of the correction technique. Again, the algorithm presents an adequate representation of the

actual composition based upon the protocol defined in this report.

### **EOS Calculated PVT Properties of Corrected Fluid**

The PVT properties of the corrected reservoir fluid were calculated using the modified Peng-Robinson Equation of State<sup>1</sup> and tuning the parameters to match the measured data obtained from differential liberation with the reservoir fluid as received. For the viscosity study, the Pedersen’s Corresponding Method correlation (1984)<sup>2</sup> was used. The PVT properties of uncontaminated and contaminated samples are shown in Tables 3 through 5 and in Figures 17 through 20.

All calculations were performed using the cubic EOS based Software WinPROP, CMG Modelling Group Ltd.

The trends with deconvolving the contaminated samples were, in going from contaminated sample (4.89) to clean oil:

1. Formation volume factor increased from 1.237 to 1.277 at the bubble point.
2. GOR increased from 315 to 353 scf/bbl at the bubble point.
3. Density went from 0.730 to 0.726 g/cc at the bubble point.
4. Viscosity decreased from 0.523 to 0.518 cP at the bubble point (this had the least accuracy in the comparison between EOS and data and, therefore, is thought to be the least reliable).

### **SUMMARY**

1. Two techniques were explored for the deconvolution of drilling fluid contamination from reservoir fluid: one was suited to a narrow distribution of contaminant components and one technique to a much broader distribution.
2. Once the degree of contamination is determined, standard techniques were used to correct for the influence of contamination on standard PVT properties such as Bo,  $\rho$ , GOR,  $\mu$ .

3. The more difficult of the two techniques was tested on two blind tests: cases where the contamination level was known and the algorithm used to determine the level of contamination. In the first blind test, the target was 20.46 mass % and the algorithm calculated 21.0 mass %. In the second assay, the seed value was 10.4 mass % with the algorithm calculating 9.6 mass %.
4. The influence of mud filtrate contamination was that as the filtrate contamination increased, the measurement of Bo would be too low,  $\rho$  too high, GOR too low and viscosity too high.
5. These techniques were developed for the circumstance that uncontaminated oil was entirely unknown and that clean oil parameters would have to be generated from contaminated samples.

## NOMENCLATURE

FVF	Formation volume factor
GOR	Solution or liberated gas-oil ratio, as specified (default: solution gas-oil ratio)
$P_{pc}$	Pseudo-critical pressure
$P_{sat}$	Bubble point pressure
$T_{pc}$	Pseudo-critical temperature
$V_{sat}$	Fluid volume at saturation pressure
Z	Gas deviation factor

## REFERENCES

1. Peng, D.Y. and D.B. Robinson, "A New Two Constant Equation of State", Ind. Eng. Chem.. Fundamentals, 15, 59 (1976).
2. Pedersen, K.S., Aa. Fredenslund, P.L. Christensen, and P. Thomassen, Chem. Eng. Sci. 39, 1984, 1011.
3. Pedersen, K.S. and Aa. Fredenslund, Chem.. Eng. Sci. 42, 1987, 182.

Component	Mass Fraction	
	Computed	Target
C3	0.0000	0.0007
i-C4	0.0001	0.0005
n-C4	0.0017	0.0045
i-C5	0.0000	0.0041
n-C5	0.0049	0.0084
C6	0.0142	0.0191
C7	0.0414	0.0448
C8	0.0354	0.0350
C9	0.0331	0.0317
C10	0.0417	0.0424
C11	0.0511	0.0499
C12	0.0534	0.0503
C13	0.0549	0.0537
C14	0.0541	0.0483
C15	0.0436	0.0455
C16	0.0439	0.0421
C17	0.0493	0.0433
C18	0.0412	0.0364
C19	0.0335	0.0332
C20	0.0326	0.0297
C21	0.0293	0.0274
C22	0.0262	0.0253
C23	0.0235	0.0227
C24	0.0205	0.0200
C25	0.0197	0.0181
C26	0.0168	0.0175
C27	0.0155	0.0154
C28	0.0147	0.0147
C29	0.0123	0.0136
C30+	0.1788	0.1736
Blind Test - 20.46 Mass % Filtrate		

**Table 1: Compositions of Corrected Oil and Actual Oil**

Component	Mass Fraction	
	Computed	Target
C3	0.0000	0.0008
i-C4	0.0001	0.0006
n-C4	0.0024	0.0051
i-C5	0.0032	0.0042
n-C5	0.0065	0.0084
C6	0.0176	0.0188
C7	0.0427	0.0453
C8	0.0379	0.0357
C9	0.0331	0.0331
C10	0.0408	0.0440
C11	0.0478	0.0502
C12	0.0487	0.0506
C13	0.0518	0.0527
C14	0.0509	0.0467
C15	0.0428	0.0445
C16	0.0419	0.0407
C17	0.0472	0.0418
C18	0.0409	0.0352
C19	0.0289	0.0322
C20	0.0307	0.0292
C21	0.0278	0.0272
C22	0.0253	0.0255
C23	0.0230	0.0231
C24	0.0205	0.0205
C25	0.0200	0.0186
C26	0.0176	0.0181
C27	0.0165	0.0159
C28	0.0163	0.0153
C29	0.0144	0.0142
C30+	0.1790	0.1736
Blind Test - 10.40 Mass % Filtrate		

**Table 2: Compositions of Corrected Oil and Actual Oil**

Pressure [psia]	Oil FVF [bbl/STB]	RS [SCF/STB]	Oil Density [g/cc]	Oil Viscosity [cp]
6013	1.1818	314.79	0.7645	0.642
5013	1.1906	314.79	0.7589	0.620
4013	1.2001	314.79	0.7529	0.589
3013	1.2106	314.79	0.7463	0.570
2013	1.2226	314.79	0.7390	0.545
1513	1.2294	314.79	0.7349	0.533
1190	1.2344	314.79	0.7319	N/A
<b>994</b>	<b>1.2374</b>	<b>314.79</b>	<b>0.7302</b>	<b>0.523</b>
913	1.2296	296.54	0.7323	0.547
763	1.2149	264.89	0.7368	0.571
613	1.2003	232.19	0.7412	0.616
463	1.1847	197.94	0.7457	0.651
313	1.1661	157.53	0.7507	0.685
163	1.1404	109.76	0.7580	0.745
88	1.1104	66.09	0.7673	0.861
27	1.0840	25.18	0.7727	1.173
13	1.0635	0.00	0.7779	1.297

**Table 3: Measured Properties of Contaminated Fluid**

Pressure [psia]	Oil FVF [bbl/STB]	RS [SCF/STB]	Oil Density [g/cc]	Oil Viscosity [cp]
6013	1.1854	320.50	0.7666	0.9711
5013	1.1941	320.50	0.7610	0.8854
4013	1.2041	320.50	0.7547	0.7983
3013	1.2158	320.50	0.7475	0.7105
2013	1.2297	320.50	0.7390	0.6230
1513	1.2377	320.50	0.7342	0.5798
1190	1.2434	320.50	0.7309	0.5522
<b>996</b>	<b>1.2470</b>	<b>320.50</b>	<b>0.7288</b>	<b>0.5357</b>
994	1.2467	319.97	0.7288	0.5362
913	1.2371	300.68	0.7318	0.5521
763	1.2190	264.82	0.7375	0.5846
613	1.2005	228.80	0.7435	0.6219
463	1.1810	191.99	0.7498	0.6657
313	1.1595	152.89	0.7568	0.7205
163	1.1315	106.09	0.7655	0.8010
88	1.1111	75.03	0.7714	0.8663
27	1.0699	22.12	0.7811	1.0045
15	1.0510	0.00	0.7849	1.0740

**Table 4: Calculated Properties of Contaminated Fluid**

<b>Pressure [psia]</b>	<b>Oil FVF [bb/STB]</b>	<b>RS [SCF/STB]</b>	<b>Oil Density [g/cc]</b>	<b>Oil Viscosity [cp]</b>
6013	1.2133	353.47	0.7646	0.9348
5013	1.2223	353.47	0.7589	0.8526
4013	1.2327	353.47	0.7525	0.769
3013	1.2448	353.47	0.7452	0.6848
2013	1.2594	353.47	0.7366	0.6009
1513	1.2678	353.47	0.7317	0.5594
1190	1.2737	353.47	0.7283	0.5329
1002	1.2773	353.47	0.7262	0.5176
994	1.2763	351.43	0.7265	0.5191
913	1.2662	331.36	0.7295	0.5344
763	1.2473	294.05	0.7354	0.5658
613	1.228	256.58	0.7414	0.6016
463	1.2077	218.28	0.7478	0.6437
313	1.1852	177.55	0.7549	0.6964
163	1.1557	128.61	0.7638	0.7742
88	1.134	95.89	0.7698	0.8377
27	1.0894	38.91	0.7800	0.9756
15	1.0685	14.57	0.7840	1.0471

**Table 5: Calculated Properties of Cleaned\* Fluid**

\*Cleaned – meaning after the computed mass fraction of mud filtrate was removed from the EOS tuned to the contaminated sample data.

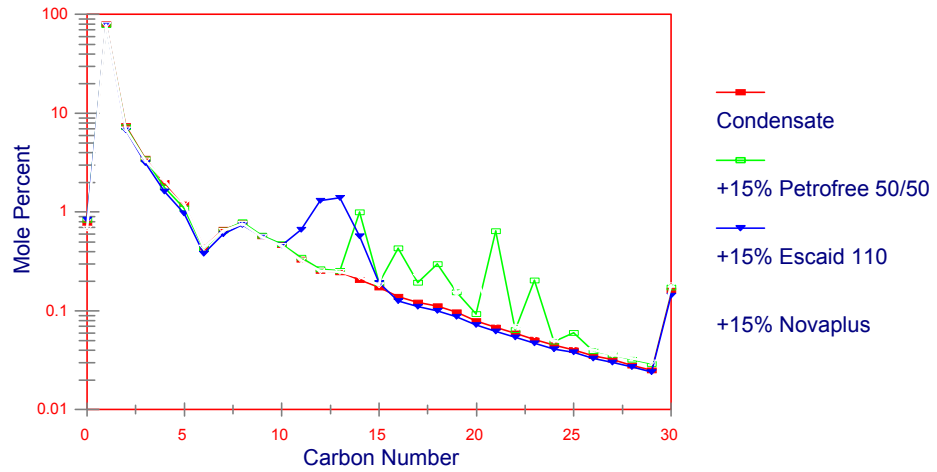


Figure 1: In-situ Reservoir Fluid and Different Contaminants

Best Fit of Moles vs Carbon Number

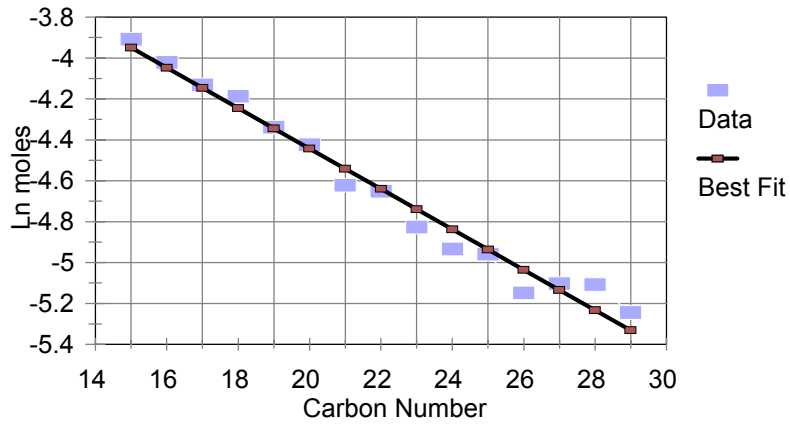
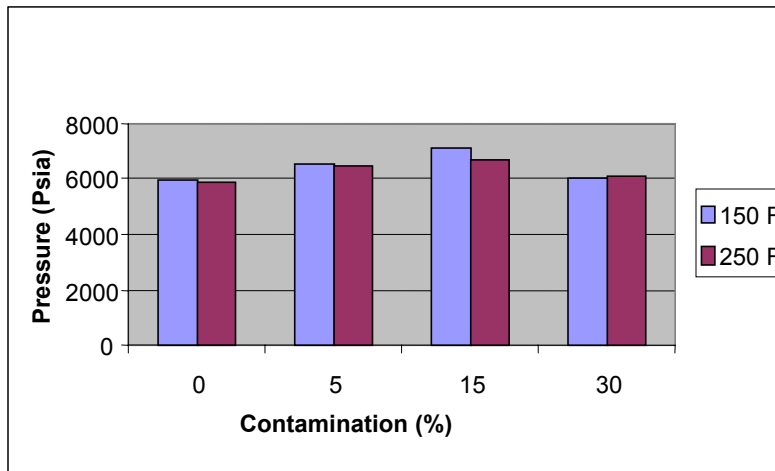
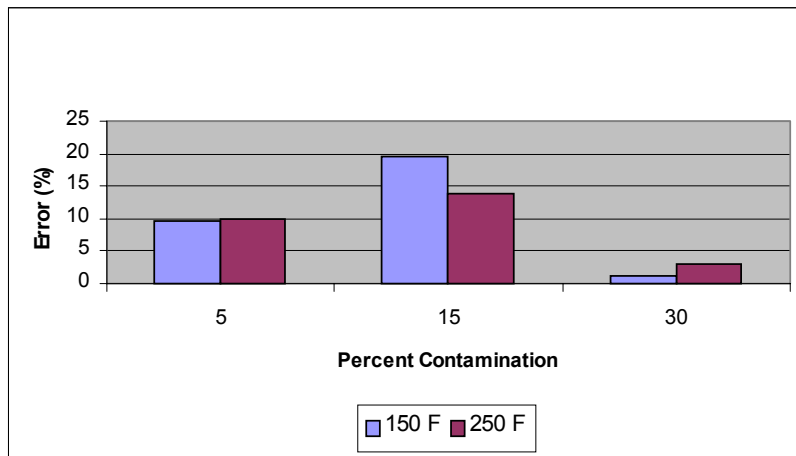


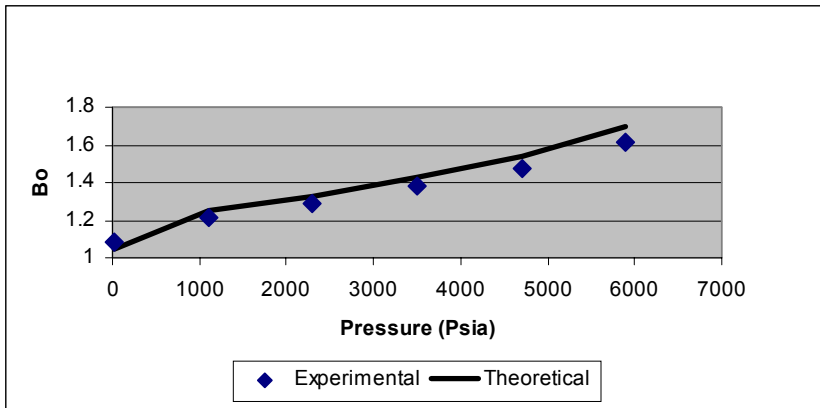
Figure 2: Measurement of Moles of Reservoir Fluid



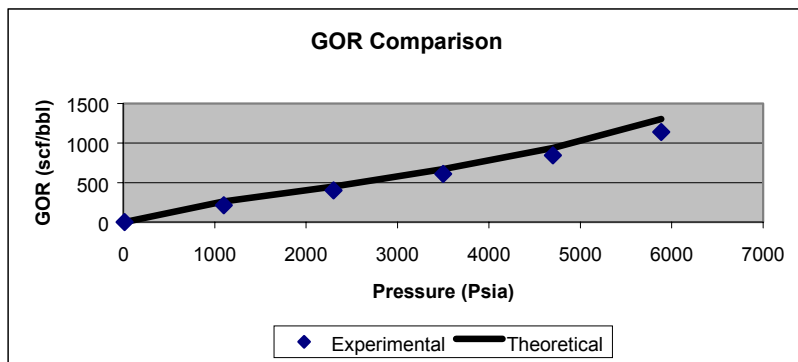
**Figure 3: Theoretical Predictions of Base Oil Bubble Point**



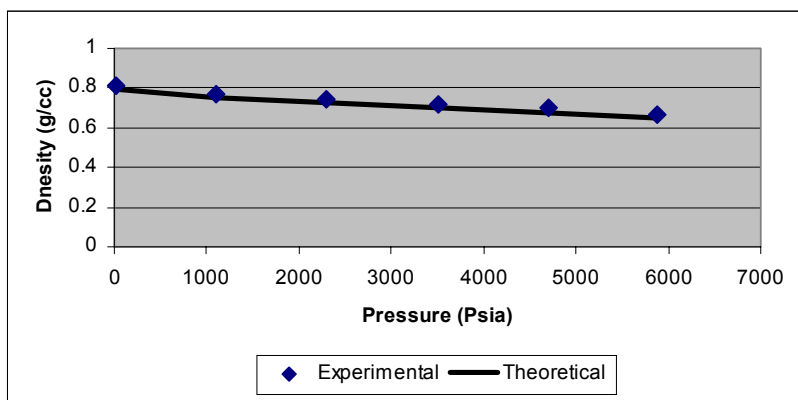
**Figure 4: Error in Bubble Point Calculation**



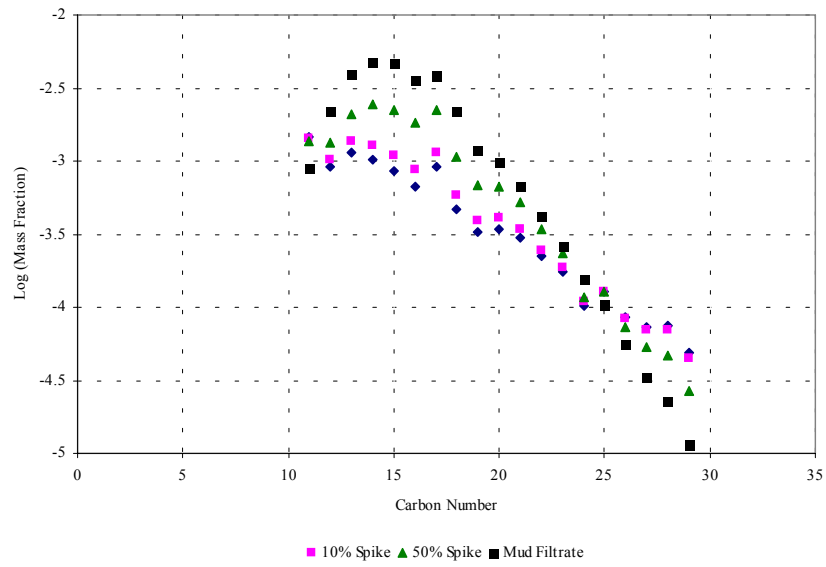
**Figure 5: Formation Volume Factor Comparison**



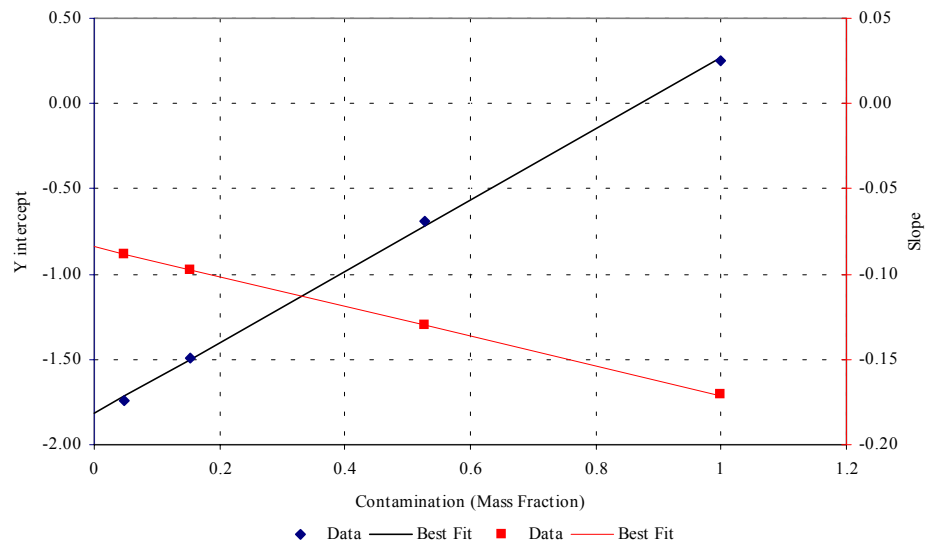
**Figure 6: GOR Comparison**



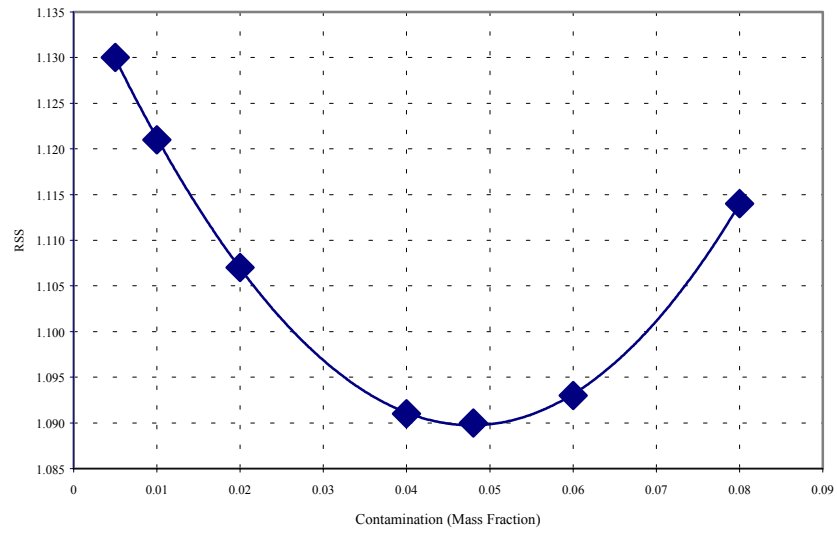
**Figure 7: Density Comparison**



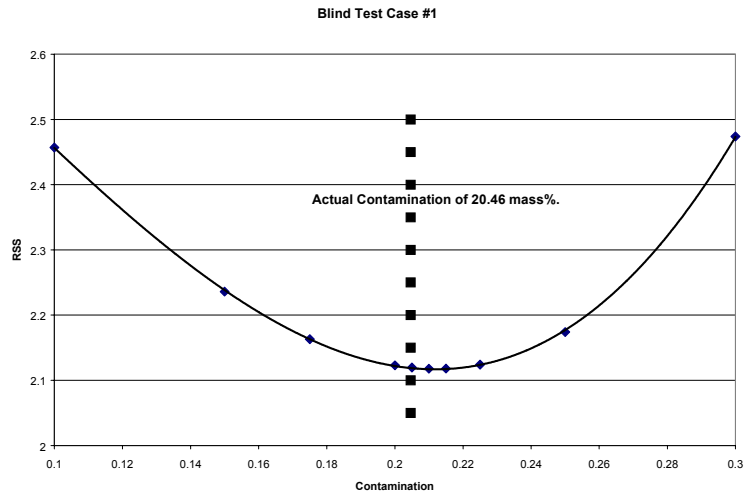
**Figure 8: Compositional Analysis of Contaminated Fluids**



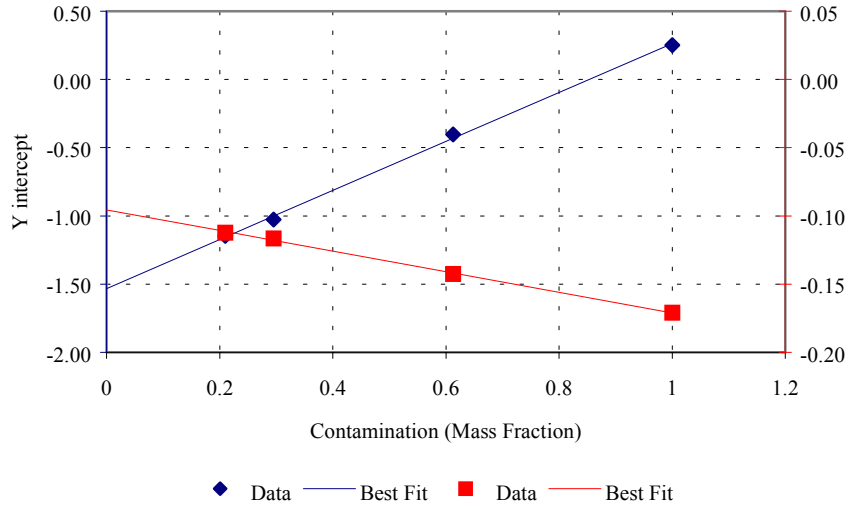
**Figure 9: Relationship of Intercept and Slope**



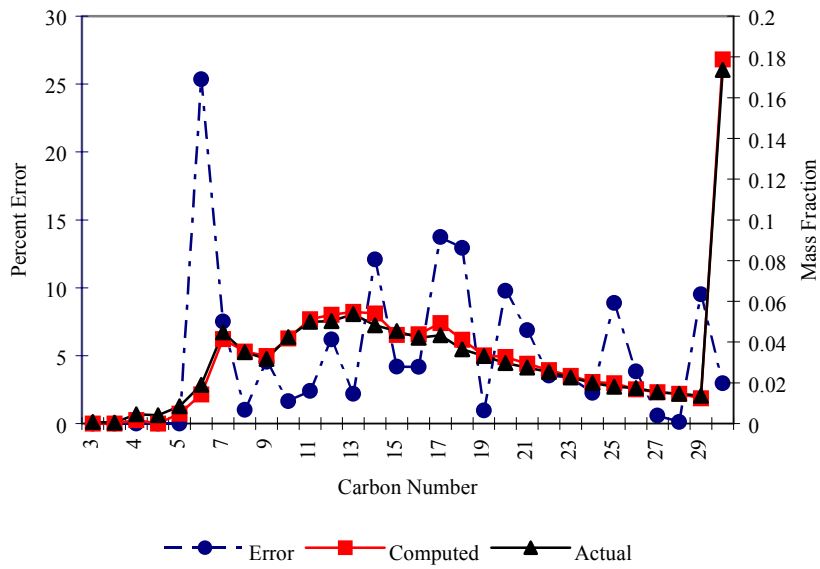
**Figure 10: Objective Function Value**



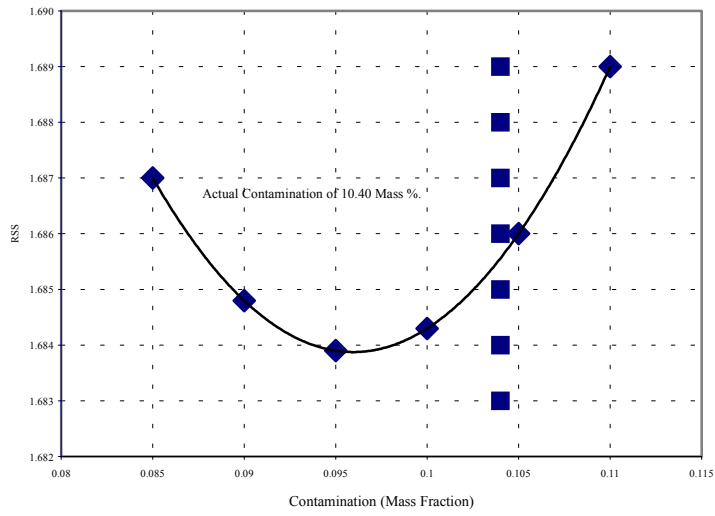
**Figure 11: Objective Function Value (Blind Test)**



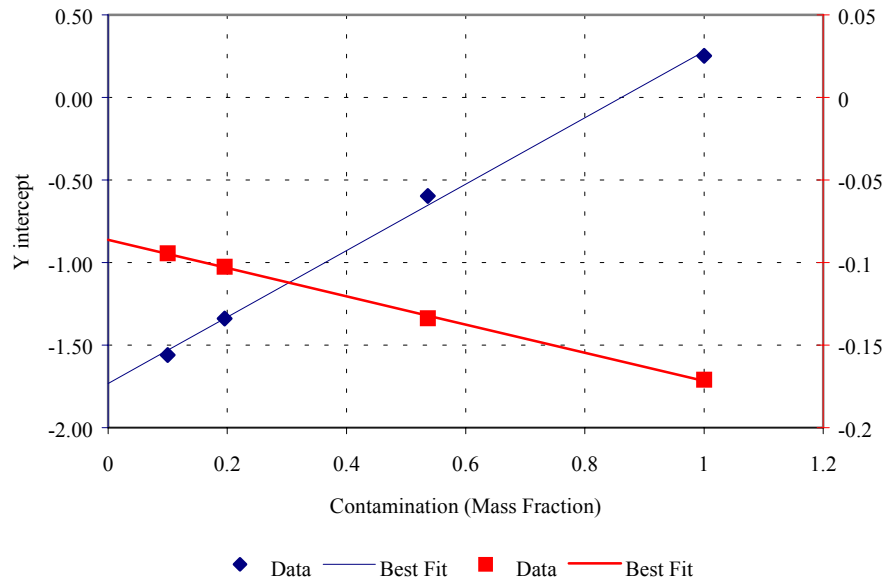
**Figure 12: Relationship of Intercept and Slope (Blind Test)**



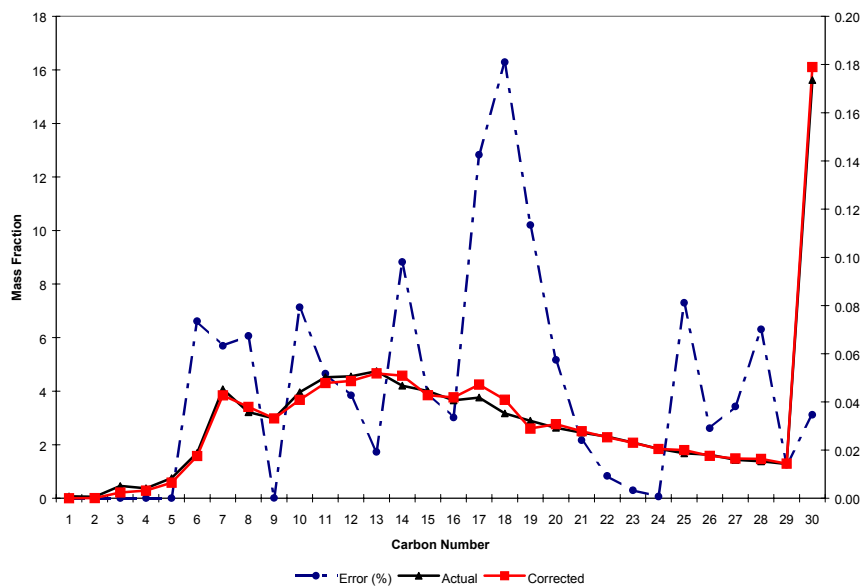
**Figure 13: Mass Fraction Comparison (Blind Test)**



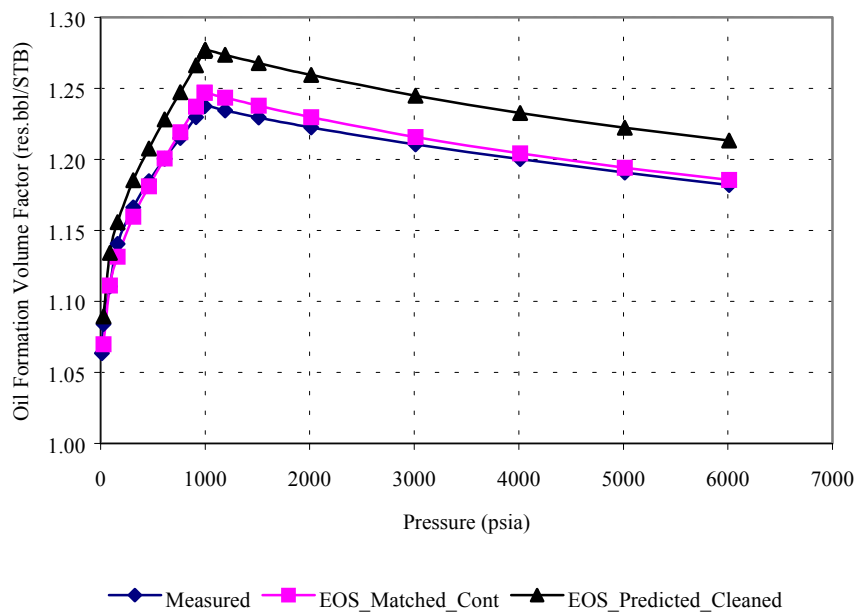
**Figure 14: Objective Function Value (Blind Test)**



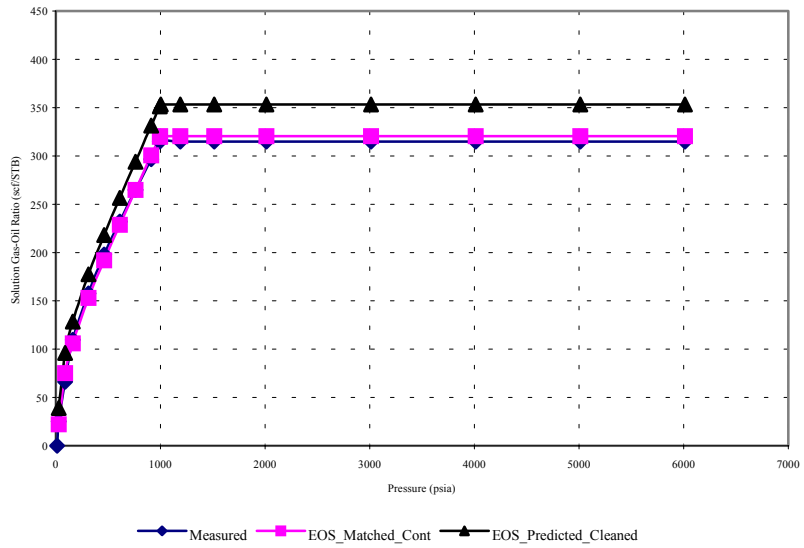
**Figure 15: Relationship of Intercept and Slope (Blind Test)**



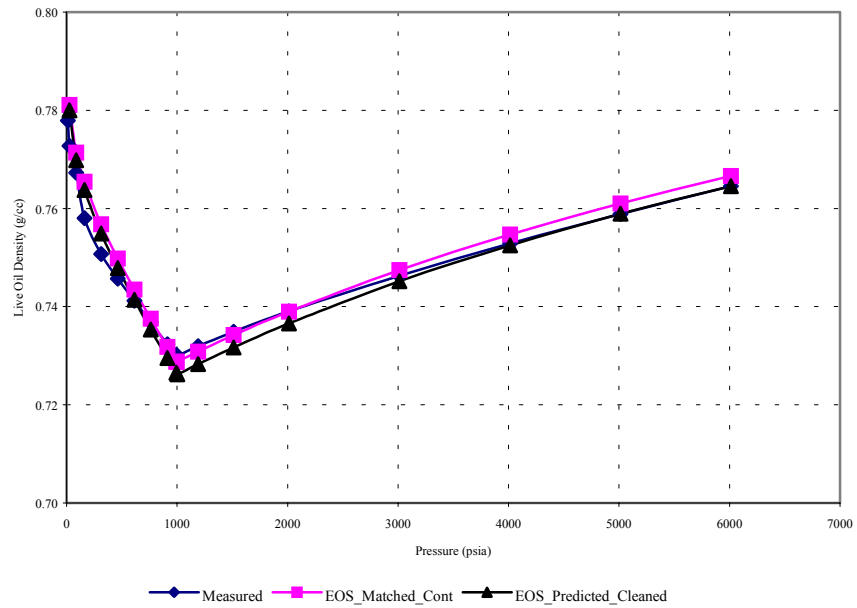
**Figure 16: Mass Fraction Comparison (Blind Test)**



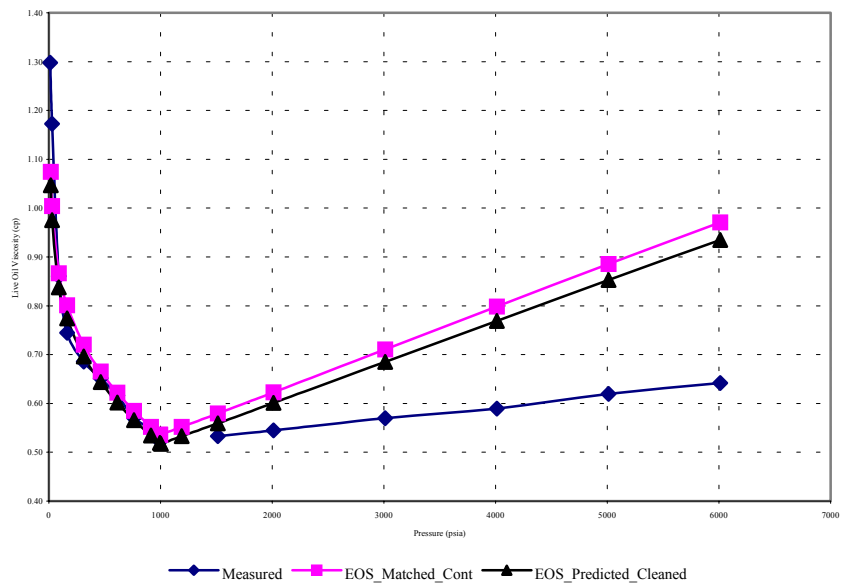
**Figure 17: Oil Formation Volume Factor**



**Figure 18: Solution Gas-Oil Ratio**



**Figure 19: Live Oil Density**



**Figure 20: Live Oil Viscosity**