

Oil-Base Mud Contamination in Gas-Condensate Samples

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Executive Summary

When wells are drilled with oil-based mud (OBM), the hydrocarbons in the OBM will usually enter the reservoir during drilling, due to the mud column exceeding reservoir pressure. When samples are taken from these wells with open-hole samplers, such as the MDT and RCI tools, the fluids will be contaminated with components from the OBM.

The impact of OBM contamination on gas condensate samples is not well understood, as very little published data are available, and the effects of contamination are more complex than for reservoir oils. The use of OBM-contaminated gas condensate samples becomes questionable at best, and certainly not ideal for defining initial condensate yields, or for developing an Equation of State model to describe the in-situ fluid system.

This project aims to give an improved understanding of near-well flow during open-hole sampling of contaminated gas condensate wells, and of the phase behaviour of OBM gas condensate mixtures. A detailed 3-D compositional simulation model was used to study near-well flow during open-hole sampling of a well that has been contaminated with OBM, and to investigate how contamination levels are affected by parameters such as reservoir fluid properties, OBM composition, rock properties and sampling conditions. The results from the simulations were used to investigate methods for back-calculating original reservoir fluid compositions from contaminated samples.

The most important conclusions from this project are

1. The most significant parameters in determining the OBM contamination levels are the level of OBM penetration during drilling, the cumulative production during clean-up and the k_v/k_h ratio. Other parameters, such as heterogeneity, drawdown, the flow area to the well, and the relative permeability are less important.
2. Contamination levels are higher for leaner fluids, but only because of the definition of contamination as a weight fraction of the dead condensate. The OBM mol fraction in the wellstream does not vary greatly with reservoir fluid.
3. It is still possible to obtain accurate samples even when the flowing bottom hole pressure is below the dew point pressure, provided that the well has flowed for long enough for the condensate bank to stabilize.
4. Large rate changes should be avoided prior to sampling, even when the flowing bottom hole pressure is below the dew point. Reductions in the production rate lead to 'unloading' of the condensate bank, increasing the concentration of liquid components in the wellstream.
5. Decontamination procedures were developed by fitting the molar distribution to exponential or gamma functions, using both an Excel spreadsheet and PVT software. These procedures were able to provide accurate estimates of the reservoir fluid composition from contaminated sample compositions. PVT calculations on the 'decontaminated' fluid compositions gave practically the same results as for the original fluid composition.

1 Introduction

When wells are drilled with oil-based mud (OBM), the hydrocarbons found in the OBM will usually enter the reservoir during drilling, due to the mud column exceeding reservoir pressure. Mixing of the OBM with reservoir fluid results in a near-well fluid that does not represent the in-situ reservoir fluid. Sampling these near-well fluids with open-hole samplers, such as the MDT and RCI tools, typically results in contaminated samples with incorrect amounts of the components found in the OBM, varying from a few to 30 weight per cent levels of contamination[§].

OBM-contaminated samples do not represent in-situ compositions, and the PVT properties measured on such samples are often quite different from in-situ fluids. For reservoir oils, it is well known that OBM contamination results in samples with Gas-Oil Ratios too low, oil Formation Volume Factors too low, and bubble points which are often low by 2 to 4 bar per weight per cent contamination. The fact that OBM hydrocarbons are miscible with most oils results in a relatively 'simple' alteration of in-situ composition and PVT properties which can often be backed-out to yield a reasonable estimate of the in-situ oil.

The impact of OBM contamination on gas condensate samples is not well understood, as very little published data are available, and the effects of contamination may be more complex than for reservoir oils. The addition of OBM hydrocarbons to a gas condensate can lead to an increase in dew point pressure, resulting in a possible phase split at initial reservoir pressure. The OBM hydrocarbon components may partition in different amounts in the resulting equilibrium gas and oil. When samples are collected by local drawdown near the well, it is unclear what mix of the contaminated equilibrium gas and equilibrium oil will enter the sampler. The resulting sample may have a dew point too high or too low, and the gas condensate liquid yield may be different from the in-situ fluid. The use of OBM-contaminated gas condensate samples becomes questionable at best, and certainly not ideal for defining initial condensate yields, or for developing an Equation of State (EoS) model to describe the in-situ fluid system.

This project aims to give an improved understanding of near-well flow during open-hole sampling of contaminated gas condensate wells, and of the phase behaviour of OBM gas condensate mixtures. A detailed 3-D compositional simulation model was used to study near-well flow during open-hole sampling of a well that has been contaminated with OBM, and to investigate how contamination levels are affected by parameters such as reservoir fluid properties, OBM composition, rock properties and sampling conditions. The results from the simulations were used to investigate methods for back-calculating original reservoir fluid compositions from contaminated samples.

[§] In this report, the OBM contamination is defined as the mass fraction of OBM in the C7+ part of wellstream fluid.

2 Characteristics of Openhole Sampling

A major difficulty when sampling with wireline testers is contamination with mud filtrate during drilling. Modern formation testers, such as Schlumberger's MDT tool¹, allow the engineer to monitor the properties of the fluid entering the flow line using measurements or optical properties. In principle, the formation fluid can be returned to the wellbore until it is representative of the formation, allowing the collection of high quality samples. In practice the contamination may continue to be significant for several days or more, especially in gas condensate reservoirs where small amounts of contamination can have a major impact on fluid properties. One of the objectives of this study is to investigate the rate of decline of contamination levels during openhole sampling.

Another problem, especially in low permeability reservoirs, is that the sampling pressure may be below the dewpoint pressure, so that some of the liquid components are condensed around the well, resulting in samples that are leaner than the reservoir fluid. Another objective of this study is to look at the significance of sampling below dew point, and whether it is possible to improve sample quality by changes in production rate before sampling.

Reference 1 contains full details of the MDT tool, and the various modules used for sampling. The essential features for setting up a numerical simulation model are a 'pumpout module' to collect fluids during the clean-up period before sampling, a number of 'sample modules' are used to collect reservoir fluid samples for analysis, and a 'probe module' which connects the tool to the reservoir. The area for flow from the reservoir into the probe module is relatively small, with linear dimensions of a few centimetres.

3 Fluids

3.1 Reservoir Fluids

Two different EoS models were set up to represent the reservoir fluids for this study. The first model was based on the fluid from the Third SPE Comparative Solution Project ², and the second model on the NS-1 gas-condensate described by Whitson and Torp ³.

3.1.1 SPE3 fluids

The reservoir fluid from the Third SPE Comparative Solution Project is a moderately rich gas-condensate with a measured dew point pressure of 237 bar(a) at 93 deg C, and a C7+ fraction of 6.6 mol %. Reference 2 includes a compositional analysis up to C20+, and a comprehensive set of PVT measurements including Constant Volume Depletion (CVD) and Constant Composition Expansion (CCE), and a Swelling Test with a lean hydrocarbon gas.

A 24-component EoS model was set up to model this fluid. This model used lumped pseudocomponents for C1 + N2, and for C2 + CO2. Single carbon number fractions were used for C3 to C19 inclusive. The C20+ fraction was modelled with 3 pseudocomponents; C20-C23, C24-C29 and C30+, using an exponential distribution to subdivide the C20+ fraction. PVT modelling and EoS calculations for this project used the PhazeComp program from Zick Technologies ⁴.

The match to the experimental data was improved by adjusting the EoS model parameters of the C7+ components, and the binary interaction parameters between C1+N2 and the other components. The boiling points and critical properties of the C7+ components were adjusted in three groups; C7 to C14, C15 to C19 and C20+.

It was not possible to obtain a particularly good match to all of the experimental data, but the final model concentrates on providing a reasonable match to the Z-factor, moles of gas removed and C7+ mol fraction in the CVD experiment, as these data have the greatest impact on liquid and gas recoveries. The final EoS model has a calculated dew point pressure of 232 bar(a) and a C7+ mol fraction of 6.81%. (The C7+ mol fraction differs from the measured value because molecular weights of the C7+ fractions were changed during the parameter adjustment, whereas the measured weight fractions were preserved.) This fluid is termed 'SPE3' in the remainder of this report.

A second, leaner fluid was generated by using a compositional gradient calculation to estimate the fluid composition at a depth 120 m shallower than the original fluid. This fluid has a slightly lower dew point pressure of 222 bar(a) and a much lower C7+ fraction of 3.96 mol %. This fluid is termed 'SPE3L' in the remainder of this report. The SPE3 and SPE3L fluids used the same EoS parameters and component properties; only the compositions were different.

Table 1 shows the compositions of the two fluids; Figure 1 shows the calculated C7+ mol fraction in the gas phase, and Figure 2 shows the liquid saturation during a CVD experiment. The EoS parameters for this fluid are listed in Table 2.

3.1.2 NS-1 fluids

The NS-1 fluid is a rich gas-condensate fluid from a North Sea reservoir, with a measured dew point pressure of 466 bar(a) at 138 deg C, and a C7+ fraction of 8.2 mol %. Reference 3 gives a compositional analysis up to C7+ and measurements from a CVD experiment.

A 24-component EoS model was set up to model this fluid, with a similar set of components to the SPE3 EoS model. Lumped pseudocomponents were used for C1 + N2, and for C2 + CO2. Single carbon number fractions were used for C3 to C19 inclusive. The C20+ fraction was modelled with 3 pseudocomponents – C20-C24, C25-C29 and C30+. The measured C7+ fraction was split using an exponential distribution.

EoS model parameters of the C7+ components, and the binary interaction parameters between C1 and C7+, were adjusted to improve the match to the experimental CVD data. The boiling points and critical properties of the C7+ components were adjusted in a single group. The resulting EoS model gave a good match to all of the measured CVD data. This fluid is termed ‘NS-1’ in the remainder of this report.

Two leaner fluids were generated by using a compositional gradient calculation; a medium rich fluid NS-1M at a depth of 183 m shallower than the original fluid, and a lean fluid NS-1L at a depth of 670 m shallower than the original fluid. The C7+ fractions for the medium and lean fluids are 5.5 mol % and 3.3 mol % respectively. The three NS-1 fluids used the same EoS parameters and component properties, but with different compositions.

Table 3 shows the compositions of the three NS-1 fluids and Table 4 lists the EoS model parameters. Figure 3 shows the calculated C7+ mol fraction in the gas phase and Figure 4 shows the liquid saturation during a CVD experiment. Table 5 summarises the properties of the five SPE3 and NS-1 reservoir fluids.

3.2 Oil-Based Muds

Two Oil-Based Muds were used in this study – a 2-component OBM and a ‘diesel’ OBM with a wide range of hydrocarbon components.

The 2-component OBM used the same composition and properties as the DMF-3 fluid of Gozalpour *et al*⁵. This is a linear alpha olefin drilling fluid composed of 69 mol % tetradecene and 31 mol % hexadecene. The average molecular weight is 205.

The composition of the diesel OBM is shown in Table 6. The composition was generated from a gamma distribution⁶ covering the C11 to C19 range. The average molecular weight is 207. This OBM composition is similar to the DMF-1 fluid of Gozalpour *et al*⁵, but with a lower average molecular weight.

3.3 Properties of Reservoir Fluid – OBM Mixtures

The EoS models were used to calculate PVT properties of mixtures of reservoir fluids and OBMs at different levels of contamination. In this report we define the contamination in terms of the wellstream fluid composition

$$\text{contamination} = \frac{\text{mass of OBM in 1 mol of wellstream fluid}}{\text{mass of C7 + components in 1 mol of wellstream fluid}} \quad (1)$$

Note that the ‘mass of C7+ components’ in the denominator of equation 1 includes the OBM components. For practical purposes, this definition corresponds to the mass fraction of OBM in the dead condensate.

Figure 5 and Figure 6 show the saturation pressures of OBM – reservoir fluid mixtures, as a function of the level of OBM contamination. The solid squares show the critical points, marking the boundary between dew point pressures to the left and bubble point pressures to the right. The contamination level needed to change the well stream fluid from a gas-condensate to a volatile oil varies from 17% for the rich SPE3 fluid to over 70% for the leanest NS1 fluid.

The results show that the saturation pressure of the SPE3 fluids increases when contaminated with OBM, whereas the saturation pressure of the NS-1 fluids decreases when contaminated with OBM. This is simply because the three NS-1 fluids have a much higher dew point pressure than the SPE3 fluids. Figure 7 shows the saturation pressures for mixtures of the 2-component OBM with equilibrium gases from a CVD experiment on the NS-1 fluid. (Note that Figure 7 is plotted in terms of the mol fraction of OBM, rather than the contamination.) These gases have dew point pressures ranging from 138 to 466 bar, but all of the saturation pressure curves converge at an OBM mol fraction of 10% and a saturation pressure of about 310 bar.

4 Numerical Model of the Near-Well Region

4.1 Introduction

A series of detailed single well simulation models were set up to model near-well flow during open-hole sampling of a contaminated well. The modelling work was carried out using the Sensor compositional simulator from Coats Engineering Inc ⁷. The simulations used detailed EoS models, as discussed in the previous section, with 22 or 24 components to represent the reservoir fluid and OBM. Appendix 1 gives a Sensor input data set for the Base Case. The Product Stream Management software from Pera a/s ⁸ was used as a post-processor to produce data for wellstream fluid compositions as a function of time.

During open-hole sampling, fluid flows into the sample vessel through a very small area, with linear dimensions of a few centimetres. The flow regime close to the well is close to spherical. A very fine grid is needed in the region close to the well to model the flow accurately.

The models used a 3-D r - θ - z grid with around 6000 grid cells, to model a cylindrical volume with a vertical interval of about 9 metres and an external radius of about 300 metres. The size of the model can be halved because of symmetry across a vertical plane through the middle of the sampling tool.

The region around the well was contaminated with OBM to a distance of between 5 and 13 cm from the well. The well was then produced through a small area to represent the sampling tool. A clean up period of up to 6 hours was allowed before the sample was taken, with production rates of around 1 litre/min.

These models were used to study the reduction in contamination levels of the wellstream sample during the clean-up period, and to examine how contamination levels are affected by parameters such as reservoir fluid properties, OBM composition, rock properties and sampling conditions. The simulation results also provided contaminated sample compositions to test different procedures for 'decontamination' - estimating original reservoir fluid compositions from contaminated samples.

4.2 Simulation Grid

The 'base case' model, which was used for almost all of the simulation runs, used 5952 cells on a 24 x 8 x 31 (r - θ - z) grid. The grid dimensions are listed in Table 7. The wellbore radius was 11.4 cm. Figure 8 gives a map of the central area of the grid in the horizontal plane, showing how symmetry was used to reduce the number of grid cells by only modelling half of the near-well region. Figure 9 shows the central area of the grid in the vertical plane.

The 'well connection' to represent the flow area during cleanup and sampling is shown in Figure 8. The flow area has dimensions of about 5 cm in both vertical and horizontal directions, giving a flow area of about 25 cm². (In the simulation model this area is halved because of symmetry.)

Before selecting the grid, a number of simulations were run with coarser and finer grids. One case was run with over 20,000 grid cells, and the results of this case are discussed in Section 5. The chosen grid offers a reasonable compromise between the need for accurate modelling while keeping run times of a few hours on a standard PC.

4.3 Numerical solution issues

The Sensor simulator offers a choice between IMPES and fully implicit solution methods. The fully implicit method is often faster for radial models with very small grid cells near the well, but the CPU time for the linear solver increases rapidly with the number of components in a fully implicit formulation. Test cases with 8 components showed that the fully implicit method needed about twice as much CPU time as IMPES. With 22 or 24 components, the fully implicit method would compare even less favourably with IMPES.

Sensor contains logic to calculate the maximum stable timestep size in an IMPES simulation. This limit was used to control the timestep size after the 'well' was opened, or after a rate change. Otherwise, it was possible to relax the stable timestep size by a factor of 2 without affecting the stability of the solution. The IMPES calculations required between 5,000 and 20,000 timesteps to simulate 6 hours clean-up and sampling. These numbers correspond to average timestep lengths of 4 seconds and 1 second respectively.

4.4 Tracking OBM components

Two different techniques were used for modelling the flow of OBM components in the simulation models. The 2-component OBM was modelled by adding 2 extra components to represent the C14 and C16 olefins. When added to the 22 components used to model the reservoir fluids, this gave a total of 24 hydrocarbon components in the compositional simulation model.

The diesel OBM contains components in 10 Single Carbon Number groups. It was not possible to add 10 extra OBM components, as Sensor is limited to a maximum of 24 components. Instead, the tracer option in Sensor was used to track the movement of OBM components.

10 tracers were defined to correspond with the 10 components from C11 to C20-24. For example, consider the tracer associated with C15. The tracer fraction in a grid cell can vary between 0 and 1, and represents the fraction of the amount of C15 in the cell which is OBM. Sensor reports the tracer fractions in each grid cell and in the wellstream fluid. The OBM component fractions in the wellstream can be calculated by combining results for the wellstream composition and the 10 tracer fractions in the wellstream.

4.5 Initialising OBM

For most of the simulation runs, the model was initialised with OBM in the region closest to the well. Grid cells 1 to 4 in the radial direction contained OBM and irreducible water, and all other cells contained reservoir fluid and irreducible water. This gives a sharp interface between the contaminated and uncontaminated regions, with a step change in OBM contamination from 100% to 0% at about 10 cm from the well.

A sensitivity case was run with the OBM introduced by 'injection'. In this case the model was initialised with no OBM, but OBM was introduced through an 'injection well' with completions in all layers. After the required volume of OBM had been injected, the 'injection well' was shut in to restore pressure equilibrium. The 'well connection' in layers 15 to 17 was then opened to represent the clean-up and sampling period.

Introducing the OBM through the injection well gives a smoother variation in the initial OBM contamination with distance from the well, as shown in Figure 10. It is not clear which of these profiles is more realistic, as the smearing of the initial OBM in the injection well case may be due to numerical dispersion effects. In any case, the method of introducing the OBM did not have a large effect on the contamination profiles during sampling.

5 Simulation Results

5.1 Summary of all simulation cases

Table 8 lists the sensitivities studied during the single-well simulation calculations. The second column lists the parameters which were varied, and the third column shows the 'base case' value for the parameter. The remaining columns show the alternative values for the parameter.

It was not possible to run all possible combinations of all parameters, but each parameter variation was examined at least once. Some of the more important sensitivities were examined with more than one combination of the other parameters.

Table 9 lists the simulation cases that were run for this study, together with the contamination at the end of the run. The 'Case Title' gives a reference to the sensitivities listed in Table 8. For example, Case 'A3C2' uses the NS1 reservoir fluid (Row A, sensitivity 3 in Table 8) and diesel OBM (Row C, sensitivity 2 in Table 8). All parameters that are not specified in the Case Title take their base case values.

The results from the different cases were assessed by comparing the OBM contamination in the wellstream fluid as a function of time, and the wellstream fluid composition at the end of the simulation.

5.2 Reduction on contamination during clean-up

Figure 11 shows the variation of the OBM contamination in the wellstream fluid with time, during the 6 hour clean-up period, for the base cases with the five different reservoir fluids. Results for all of the other cases show a similar behaviour for the reduction in OBM contamination during clean-up.

Figure 12 compares results for Case A1 (the Base Case with SPE3 fluid) and Case A1H2, where the production rate was halved from 1 litre/min to 0.5 litre/min, and the clean-up period lasted for 12 hours instead of 6. These results show that the reduction in contamination is a function only of the cumulative production.

Charts were produced for OBM contamination and OBM mol fraction versus time on log-log and semilog plots, in an attempt to develop a simple approximation to extrapolate OBM contamination in time, using results from Case A1H2, which was run for a 24-hour clean-up period.

The best match for the OBM concentration was a semilog plot with time plotted on a log scale, as shown in Figure 13. A straight line gives a reasonable fit to the simulation results between about 8 seconds and 1 hour, but becomes much less accurate after 1 hour, the period when sampling is likely to take place.

The best match for the OBM mol fraction was a log-log plot as shown in Figure 14. There is an initial period of between 1 and 20 seconds before reservoir fluid breaks through to the well, followed by a further few seconds while the OBM fraction declines rapidly as the OBM is cleaned out very close to the well. After then, a straight line gives a reasonable fit to the simulation results up to about 10 hours, although it is less accurate. These results suggest that the log-log plot of OBM mol fraction is the best way of extrapolating the reduction in OBM contamination levels with time.

5.3 Gridding issues

Some of the results in Figure 11 show ‘bumpy’ profiles for the decline in OBM contamination during clean-up. This is thought to be due to gridding effects, where a radial grid is being used to model what is very close to spherical flow near to the well. However, these ‘bumps’ in the profile should not affect the essential features of the solution.

One additional case (A4D6F2) was run with a finer grid in the θ and z directions, using over 20,000 grid cells. A 1 md case was run as the cases with a large drawdown, and a large condensate bank, may be more sensitive to the choice of grid. Figure 15 compares the contamination profiles for this case with the corresponding case (A4F2) on the standard grid, and there is very little difference between the results.

5.4 Sensitivities to reservoir and fluid parameters

5.4.1 Reservoir fluid composition

The first five cases in Table 9 correspond to the ‘Base Cases’ for each of the five reservoir fluids. These cases assume a 2-component OBM which fills 10 cm out from the well, a homogeneous 10 md reservoir with $k_v/k_h=1$, and an initial reservoir pressure just above the dew point pressure.

The final OBM contamination levels, after 6 hours’ clean-up, range from 6.7% for NS-1 (the richest fluid) to 17.2% for NS-1L (the leanest fluid). However, these five simulations give very similar values for the OBM fractions in the wellstream fluid at the end of the simulation, ranging between 0.48% and 0.52 mol %.

These results (and similar results for the five reservoir fluids with the diesel OBM) suggest that the mol fraction of OBM in the wellstream fluid is almost independent of reservoir fluid composition, for cases where there is a relatively low drawdown so that phase behaviour effects are not important. The variation in OBM contamination with reservoir fluid is almost entirely due to the change in the denominator of equation 1 (mass fraction of C7+) between lean and rich gas condensates.

Contamination with OBM raises the dew point pressure for the SPE3 fluids, but lowers the dew point pressure for the NS-1 fluids. However, the dew point change does not appear to cause any fundamental difference in the behaviour of the OBM contamination in the wellstream fluid.

5.4.2 OBM composition

The contamination levels with the diesel OBM (cases A1C2 to A5C2 in Table 9) are significantly higher than with the 2-component OBM. The fraction of OBM in the wellstream fluid at the end of the simulation varies between 0.63 and 0.65 mol %. After a very short clean-up period during which the OBM flows into the well as a liquid phase, the OBM contamination in the wellstream is caused by OBM components being vaporised into the flowing gas phase. The amount of vaporisation will depend on the volatility of the OBM components, so it is not surprising that the contamination depends on the OBM properties.

5.4.3 Drawdown and degree of undersaturation

In the five 'Base Case' Cases A1 to A5, the reservoir fluid is almost saturated at initial conditions – the reservoir pressure is less than 1 bar above the dew point pressure. The drawdown (the difference between pressure in the main body of the reservoir and the pressure in the grid cells next to the well connections) varies between 5 and 7 bar, and there is a small 'condensate bank' close to the well, out to a distance of about 13 cm from the sandface.

In Cases A1B2 to A5B2, the initial reservoir pressure is about 7 bar above the dew point pressure, which is high enough to prevent the formation of a condensate bank around the well. The increase in initial pressure has only a minimal effect on the levels of OBM contamination in the wellstream.

In Cases A1F2 to A5F2, the permeability is reduced from 10 md to 1 md. The production rate of 1 litre/min was maintained, so the drawdown increased to around 70 bar. A larger condensate bank forms around the well, out to a distance of about 28 cm from the sandface for case A1F2, and somewhat smaller for the other fluids. The large drawdown increases the contamination level significantly for the rich SPE3 fluid (13% compared with 10.3%), and to a smaller extent for the other fluids. The OBM fraction in the wellstream fluid is 0.66 mol % for SPE3, and between 0.52 and 0.54 mol % for the other four fluids. It appears that the impact of the condensate bank caused by the higher drawdown is greatest for fluid SPE3, which has the largest condensate bank and the highest liquid saturation within the bank.

5.4.4 k_v/k_h

Cases A1G2 and A3G2 were used to test the sensitivity to the vertical / horizontal permeability ratio k_v/k_h . Changing k_v/k_h from 1 to 0.1 reduced the final OBM contamination significantly, from 10.3% to 4.1% for SPE3 and from 6.7% to 2.7% for NS-1. The OBM fraction in the wellstream fluid reduced from 0.5 to 0.2 mol %. Figure 16 shows the oil saturations around the well for the SPE3 fluid after 6 hours clean-up, comparing the results with $k_v/k_h = 1$ and $k_v/k_h = 0.1$. For the $k_v/k_h = 0.1$ case, the condensate bank is confined more to the horizontal layers close to the sampling tool, and there is less tendency to sweep out OBM from the areas above and below.

5.4.5 OBM volume

As might be expected, the OBM contamination level increases or decreases in line with the initial volume of OBM. In the base case, OBM fills the first four cells in the radial direction, a distance of 10 cm from the sandface. In case A1J2, the initial volume of OBM is increased by 50%; OBM fills the first six cells in the radial direction, a distance of 13.5 cm from the sandface. In case A1J3, the initial volume of OBM is reduced by 50%; OBM fills the first two cells in the radial direction, a distance of 5 cm from the sandface.

The final contamination levels are 5.7%, 10.3% and 14.1% for increasing initial volumes of OBM, and the corresponding OBM mol fractions in the wellstream fluid are 0.27 mol %, 0.51 mol % and 0.73 mol %. To a first approximation, the OBM mol fractions in the wellstream fluid are proportional to the initial mass of OBM.

5.4.6 Heterogeneity

Three cases were run to assess the impact of reservoir heterogeneity. Cases A1D3 and A1D4 used layered permeabilities with the permeability in layers 15 to 17 (where the well was completed) changed to 20 md and 5 md respectively. Case A1D2 used a random variation in permeability in all grid cells. The random permeabilities were generated using a log normal distribution with a mean of 10 md and a standard deviation of 0.5. Two simulation runs were made with different sets of random permeabilities. In all cases, the introduction of heterogeneity had only a minor impact on OBM contamination levels.

5.4.7 Relative permeability

The gas-oil relative permeabilities for the Base Case were based on Corey analytic functions with an exponent of 2, and end point saturations of 0.05 for gas and 0.2 for oil. Case A1E2 was run with straight-line gas-oil relative permeabilities and zero end point saturations. Using straight-line relative permeabilities eliminates the condensate bank and reduces the drawdown by a factor of 2, but has only a minor impact on the OBM contamination. The contamination after 6 hours increases from 10.3% in the Base Case to 10.7% with straight-line relative permeabilities.

5.4.8 Method of introducing OBM

In Cases A1K2 and A3K2, the OBM was introduced by injection, to estimate the effect of changing from a 'step change' to a 'smeared' initial distribution of the OBM (as shown in Figure 10). The initial amount of OBM was the same as in the Base Case. Introducing the OBM by injection gave slightly higher levels of contamination. The final OBM contamination was 12.6% for Case A1K2 (compared with 10.3% for Case A1), and 7.8% for Case A3K2 (compared with 6.7% for Case A3)

5.4.9 Flow area to well

In Case A1M2, the flow area to the well was increased from about 25 cm² to about 100 cm². This reduced the drawdown by a factor of 2, but had very little effect on the OBM contamination.

5.5 Effect of two-phase gas-condensate flow

5.5.1 Sampling gas-condensate wells

When taking gas condensate samples it is preferable to maintain the well bottom hole pressure (BHP) above the dew point, to avoid the formation of a condensate bank around the well, which may affect the accuracy of fluid samples. In practice, it is not always possible to keep the BHP above the dew point, especially in low permeability reservoirs or where the reservoir fluid is saturated at the initial reservoir pressure. In a well contaminated with OBM, the situation may be more complex due to the OBM affecting the phase behaviour of the reservoir fluids near the well.

Results from the simulations can be used to assess the accuracy of wellstream samples under different conditions. For this part of the study we assume that a 'perfect' decontamination method is available. The OBM components are removed from the wellstream composition and the remaining composition is renormalized to give an estimated reservoir fluid composition with 'perfect' decontamination. This can be compared with the actual composition used to initialise the simulation run. The C7+ mol fraction gives a simple measure of the accuracy of the decontaminated wellstream composition.

5.5.2 Wellstream compositions with 'perfect' decontamination

Table 10 shows the C7+ mol fractions in the wellstream fluid at the end of the simulation runs, assuming 'perfect' decontamination. For the base case (10 md with near-saturated fluids) the C7+ mol fractions in the decontaminated sample are almost exactly correct, even though the BHP is several bar below the dew point pressure. For the cases using undersaturated fluids in a 10 md reservoir, there is again almost exact agreement, as would be expected because of the absence of a condensate bank. For the low permeability (1 md) cases, the decontaminated wellstream fluid is slightly too lean, although the error is quite small bearing in mind the large drawdown of about 70 bar.

The results for other components are similar to those for C7+ fraction; with almost exact agreement for the base case and for the undersaturated fluid cases.

The lower C7+ mol fraction for the 1 md cases can be explained in terms of the theory of Fevang and Whitson⁹, who describe flow to a gas condensate well in terms of three regions. Region 1 is the region closest to the well where both oil and gas phases are mobile, and when semi-steady state conditions have been reached, the wellstream composition is the same as the gas phase composition at the outer edge of Region 1. For Case A1F2 (using the SPE3 fluid in a 1 md reservoir), the pressure at the outer edge of Region 1 is about 230.7 bar, compared with the dew point pressure of 232 bar. Using the PVT data illustrated in Figure 1, the saturated fluid at this pressure has a C7+ fraction of about 6.71 mol %, compared with a value of 6.74 mol % in the wellstream fluid.

Figure 17 shows the oil saturations around the well for the SPE3 fluid after 6 hours clean-up, in the 10 md and 1 md reservoirs using saturated fluid. A condensate bank forms in both cases, although the bank is much larger for the 1 md case. Figure 18 shows the equivalent results for the NS-1 fluid. Part of the condensate bank is now removed in the region where the fluid is contaminated with OBM. This is because the addition of OBM to the NS-1 condensate leads to a **decrease** in saturation pressure (as shown in Figure 5). The same effect does not occur for SPE3 because the addition of OBM leads to an **increase** in saturation pressure.

5.5.3 Reducing the rate before sampling

When the BHP falls below the dew point during the clean-up period, the wellstream fluid may be slightly leaner than the reservoir fluid, as discussed in the previous section. In this case, the operator may consider reducing the production rate prior to sampling, in order to obtain a more representative sample.

A number of cases were run with the SPE3 fluid in the 1 md reservoir to study the impact of rate changes prior to sampling. In this case the BHP is about 70 bar below the dew point pressure, and a condensate bank has formed around the well.

In Case A1F2L2 the production rate was reduced from 10 litre/min to 1 litre/min after 6 hours clean-up. The rate change causes the BHP to increase from 165 bar to 225 bar, compared with a dew point pressure of 232 bar. Figure 19 shows the C7+ mol fraction in the decontaminated wellstream fluid after the rate change. The sudden rate change causes a large increase in the C7+ fraction, due to the production of extra liquids as the condensate bank is 'unloaded'. The wellstream composition after the rate change is much **less** representative of the reservoir fluid, even though the BHP is now much closer to the dew point pressure.

Figure 19 also shows results for two cases where the production rate was reduced more gradually from 10 litre/min to 1 litre/min. In Case A1F2L4 the rate was reduced in three steps (to 7 then 4 then 1 litre/min at 20 minute intervals), and in Case A1F2L5 the rate was reduced in nine equal steps at 10 minute intervals. These cases show smaller peaks in the C7+ fraction, and there are some periods when the C7+ fraction is closer to the reservoir fluid value, but this is probably due to cancelling errors – a leaner fluid combined with some unloading of the condensate bank.

Case A1F2L3 imposed a shut-in period of 10 minutes after 6 hours, followed by production at 1 litre/min. Results for this case were identical to Case A1F2L2 without a shut-in period, when plotted as a function of the time on production.

Figure 20 shows the OBM mol fraction for the cases where the rate was reduced prior to sampling. The OBM mol fraction shows a peak after a rate reduction, but the rate changes do not have a major impact on contamination levels.

5.5.4 Comparison of results with and without OBM

Two additional cases were run, corresponding to the base case and low permeability case for the SPE3 fluid, but with no OBM present. Figure 21 shows that the C7+ fraction of the decontaminated wellstream is almost the same as in the equivalent case with no OBM present.

The results for the high drawdown case show an initial period where the C7+ fraction in the wellstream is low; this is because of the loss of some liquid components to establish the condensate bank. After a period of about 2 hours, a semi-steady-state flow condition is achieved, after which the size of the condensate bank changes only slowly and the wellstream composition can be estimated from the Fevang / Whitson model.

5.5.5 Discussion of results

This analysis of two-phase flow around the well leads to two somewhat surprising conclusions. First, it is still possible to obtain accurate samples even when the BHP is below the dew point pressure, provided that the well has flowed for long enough for the condensate bank to stabilize. Even with a drawdown of 70 bar, the decontaminated wellstream fluid compositions are accurate enough for practical purposes.

Second, the presence of OBM does not appear to have any major impact on the composition of the decontaminated sample. If a suitable method is available for ‘removing’ the OBM components from the sample, then there appears to be no significant difference in the sample from wells with and without OBM contamination. This is a rather unexpected result in view of the complex phase behaviour of gas-condensate – OBM mixtures.

5.6 Recommended sampling method

There are two objectives during sampling of a gas-condensate well that has been contaminated with OBM. The first objective is to minimise the OBM contamination in the wellstream fluid. As a first approximation, the contamination level declines as a function of the cumulative production during the clean-up period. In order to reduce the contamination, the clean-up period should be as long as possible and the production rate should be as high as possible.

The second objective is that the ‘decontaminated’ sample (with OBM components removed) should be representative of the original reservoir fluid. Ideally, the well BHP should be kept above the dew point pressure, but this may not be possible in low permeability or near-saturated reservoirs. The need to keep the BHP above dew point may also conflict with the need to maximise the production during the clean-up period. However, the loss of accuracy from taking samples below dew point is less than might be expected, and the resulting samples may still be accurate enough for practical purposes.

A key conclusion from this part of the study is that large rate changes should be avoided prior to collecting samples. When the well BHP has fallen below the dew point pressure, it is best to avoid large reductions in production rate before sampling. Although the lower production rate will increase the well BHP, the fluid samples will be much less representative of the original reservoir fluid due to unloading of the condensate bank.

6 Decontamination Methods

In this section we discuss methods for estimating the original reservoir fluid composition from a sample contaminated with OBM. These methods rely on the fact that the molar distribution of C7+ components in a reservoir fluid can usually be fitted with some form of analytical model. The molar distribution refers to the relationship between mole fraction and molecular weight.

6.1 Exponential and gamma distribution models

In many reservoir fluids the ‘plus fraction’ – which may be the C7+ components or some subset such as C10+ - can be fitted with an exponential distribution. A plot of mole fraction versus molecular weight will give a straight line on a semi-log scale. The three-parameter gamma distribution⁶ is a more general method for describing the molar distribution of the C7+ fraction, which includes the exponential distribution as a special case.

The exponential and gamma distributions have both been used in the past to estimate reservoir fluid compositions from samples contaminated with OBM. Gozalpour *et al*⁵ used an exponential distribution while MacMillan *et al*¹⁰ used a gamma model.

6.2 Decontamination methods

There are two basic approaches for estimating decontaminated reservoir fluid compositions. The first approach, referred to as the ‘skimming’ method in Reference 5, does not require a knowledge of the OBM composition. An exponential or gamma distribution is fitted to the composition of the C7+ fraction of the contaminated sample. The resulting distribution can then be used to characterise the entire C7+ fraction, or just to define the amount of those fractions that are present in the OBM.

The other approach, described as the ‘subtraction’ method in Reference 5, relies on a knowledge of the OBM composition. An amount of OBM (say f mols) is subtracted from 1 mol of contaminated fluid to give a decontaminated sample composition. This composition is then fitted with an exponential or gamma model. The amount of OBM, f , is chosen by finding the value that minimises the standard deviation when fitting the decontaminated composition with the analytical model. This approach is suitable for all types of OBM where the composition is known.

These decontamination procedures can be applied either in a spreadsheet or using PVT software. In this study, an Excel spreadsheet was used for fitting to an exponential distribution, while the Phazecomp PVT software was used for fitting with a gamma distribution.

6.2.1 Fitting with an exponential distribution

An Excel spreadsheet was used to test the simplest decontamination method, using an exponential fit and either the ‘skimming’ or ‘subtraction’ methods. The analysis of the contaminated sample was assumed to include single carbon number (SCN) fractions up to and including C19, with a single C20+ fraction. The OBM component amounts in the wellstream were added to the corresponding SCN fraction, to try and reproduce results from gas chromatography (GC) analysis on a contaminated sample.

The mol amounts of the SCN fractions from C7 to C19 in the contaminated sample were tabulated against molecular weight and fitted with an exponential distribution, using the LOGEST function in Excel. This fitting process ignored those components that were contaminated with OBM. For the 2-component OBM, C14 and C16 were ignored. For the diesel OBM, all components from C11 to C19 were ignored.

Results from the exponential fit were then used to estimate the molar amounts of those SCN components that were contaminated with OBM. The molar amounts of other components were taken from the contaminated sample. The composition was then normalised to give the ‘decontaminated’ composition, which could be compared against the ‘correct’ reservoir fluid composition.

6.2.2 Fitting with an gamma distribution

The Phazecom PVT software was used for fitting with a gamma distribution using the ‘subtraction’ method. An example dataset is shown in Appendix 2. A regression calculation is used to adjust the three parameters in the gamma distribution, and the amount of OBM to be subtracted from the contaminated sample, so that the gamma model gives the best fit to the molar distribution of the ‘decontaminated’ sample.

6.2.3 Issues when fitting the molar distribution

There are three issues which may impact the fitting of the decontaminated distribution. The first is the choice of which components to include in the fitting process. It may be better to omit the plus fraction residue as its properties are less well defined. In this study we have only used SCN components from C7 to C19 in the fitting process, and ignored the C20+ residue. Second, the choice of the molecular weights of the SCN fractions may have some influence on the results. For this study we have assumed that the molecular weight increases by 14 between SCN groups. Finally, there is the question of how to define the ‘best fit’ to the analytical molar distribution. In the spreadsheet model we have minimised the sum of the squares of the relative errors in the SCN molar amounts. The error function is defined as

$$E = \sum_i \left(\frac{z_i}{z_{i,a}} - 1 \right)^2 \quad (2)$$

where z_i is the mol fraction of SCN component i in the decontaminated sample, and $z_{i,a}$ is the mol fraction in the analytical model. Each component is given equal weighting in the error function, regardless of the magnitude of the mol fraction.

PhazeComp offers the choice of fitting component amounts or molecular weight boundaries between the SCN groups. When fitting to component amounts, the error function is

$$E = \sum_i (z_i - z_{i,a})^2 \quad (3)$$

This places more emphasis in the fit to the components with the largest mol fractions. Fitting to molecular weight boundaries gives a more equal weighting to each component, so should give results that are closer to Equation 2.

7 Results for Decontamination of Simulated Wellstream Samples

7.1 Decontamination results

The decontamination procedures were applied to selected wellstream fluid compositions from the simulation calculations. For the SPE3 fluid, decontamination was applied to calculated wellstream samples for the richer condensate (fluid SPE3). Case A1G2 was used for the 2-component OBM, and Case A1C2 for the diesel OBM. For NS-1, decontamination was applied to samples with the leanest reservoir fluid (NS-1L) using the results from Case A5 with the 2-component OBM and Case A5C2 with the diesel OBM.

For each case, up to five samples were selected at contamination levels ranging from 10% to 50%. In some cases the contamination had not reached 10% by the end of the simulation, so that samples with 10% contamination were not available.

7.1.1 Results with an exponential distribution – SPE3 fluid

Figure 22 shows the molar distribution for the SPE3 fluid with the 2-component OBM, and Figure 23 shows the results of fitting an exponential distribution to the of 20% contaminated sample, using the ‘skimming’ method. In this case the contaminated sample shows two well-defined peaks, and fitting with the exponential distribution is very accurate, even at very high levels of contamination. Table 11 shows some details of the ‘decontaminated’ compositions, which are practically the same as the original reservoir fluid. The very small differences between the C7+ fractions in ‘decontaminated’ and reservoir fluid compositions are not due to the decontamination procedure, as the ‘decontaminated’ compositions are almost identical to the wellstream compositions with the OBM components removed.

Figure 24 shows the molar distribution for the SPE3 fluid with the diesel OBM, and Figure 25 shows the results of fitting an exponential distribution to the of 20% contaminated sample, using the ‘skimming’ method. In this case the OBM contamination covers a wide range of components, which makes the decontamination procedure less accurate. There are fewer ‘uncontaminated’ mol fractions to fit the exponential distribution (only C7 to C11 in this case), and there are more components whose mol fractions need to be estimated from the exponential fit. For the diesel OBM the mol fractions for all components from C12 to C19 need to be estimated, rather than just C14 and C16 for the 2-component OBM. Table 12 shows some details of the ‘decontaminated’ compositions. The composition is less accurate; for example the C7+ fraction is 7.1 mol % compared with a correct value of 6.8 mol%.

The accuracy of the decontamination can be improved by using the ‘subtraction’ method, where it is assumed that the composition of the diesel OBM is known. Figure 26 and Table 13 shows the results. It is now possible to fit to component amounts in the range from C7 to C19. The error in estimated C7+ fraction is only about a quarter of that with the ‘skimming’ method.

7.1.2 Results with an exponential distribution – NS-1 fluid

The exponential distribution was also to ‘decontaminate’ wellstream compositions for the NS-1L fluid with both a 2-component and diesel OBM. This fluid is a rather artificial case for testing the decontamination methods, as the composition of the original NS-1 fluid was only measured up to C7+, so the distribution of the C7+ fractions was calculated using an exponential distribution. Although the NS-1L fluid was derived from NS-1 using a compositional gradient calculation, the C7+ molar distribution is still very close to exponential.

Figure 27 and Figure 28 show the results for NS-1L samples contaminated with the 2-component OBM, and Figure 29 and Figure 30 show results with the diesel OBM. Table 14 shows some details of the ‘decontaminated’ compositions with the diesel OBM. The ‘decontaminated’ compositions with the 2-component OBM are not shown, as they are identical to the reservoir fluid compositions.

7.1.3 Results with a gamma distribution – SPE3 fluid

The PhazeComp software was used to ‘decontaminate’ wellstream compositions for the SPE3 fluid with both a 2-component and diesel OBM. PhazeComp was set up to use the ‘subtraction’ method where the composition of the OBM was specified. PhazeComp has two ways of quantifying the fit to the gamma distribution model, either comparing component amounts or molecular weight boundaries between the SCN groups.

Four decontamination calculations were made for each sample using PhazeComp – fitting with either an exponential or gamma distribution, and in each case fitting with either component amounts or molecular weight boundaries. The results are summarised in Table 15 and Table 16. For the 2-component fluid (Table 15), the results are slightly less accurate than those obtained from the spreadsheet (Table 11). The gamma and exponential distributions give very similar results. For the diesel fluid (Table 16), rather more accurate results were obtained by fitting to phase boundaries, when the results were almost identical to those obtained from the spreadsheet model using the ‘subtraction’ method. Once again, there was very little difference between the results with the exponential and gamma distributions.

7.1.4 Results with a gamma distribution – NS-1 fluid

As the molar distribution of NS1 is very close to exponential, the results for decontamination with PhazeComp were virtually identical to the reservoir fluid compositions.

7.1.5 Review of decontamination methods

The results for the SPE-3 fluid suggest that the ‘skimming’ method is better for contamination with an OBM which has a narrow range of components, while the ‘subtraction’ method is better for an OBM with a wider range of components. For this fluid, there was no advantage in fitting to a gamma model rather than an exponential distribution, although this may not be true for other reservoir fluids. When fitting to analytical molar distributions, it appears better to use a method that gives roughly equal weight to all SCN fractions in the error function.

7.2 PVT characteristics of contaminated and decontaminated samples.

To give a more practical indication of the impact of OBM contamination, some PVT properties were calculated for contaminated samples and 'decontaminated' compositions. These calculations were made for the SPE3 fluid, where there are some differences between the results of different decontamination methods.

7.2.1 SPE3 fluid contaminated with 2-component OBM

Figure 31, Figure 32 and Figure 33 show the C7+ mol fraction, liquid saturation and gas Z-factor from a simulated CVD experiment on wellstream compositions for the SPE3 fluid contaminated with the 2-component OBM, at 10% and 20% levels of contamination. At 20% contamination the fluid behaves as a volatile oil rather than a gas condensate.

Figure 34, Figure 35 and Figure 36 show the corresponding results for three 'decontaminated' fluid compositions, back-calculated from a sample with 20% contamination. Fluid 1 was calculated with the spreadsheet using the 'skimming' method. Fluids 2 and 3 were calculated with PhazeComp, assuming an exponential distribution, with Fluid 2 derived from a fit to component amounts and Fluid 3 derived from a fit to molecular weight boundaries. Table 17 compares the calculated dew point pressures and oil-gas ratios. Fluid 1 gives the best fit to the data for the original reservoir fluid, although the discrepancies for the other two fluids are unlikely to be significant in practical terms.

7.2.2 SPE3 fluid contaminated with diesel OBM

Figure 37, Figure 38 and Figure 39 show the C7+ mol fraction, liquid saturation and gas Z-factor from a simulated CVD experiment on wellstream compositions for the SPE3 fluid contaminated with the 2-component OBM, at 10% and 20% levels of contamination. In this case the 20% contaminated sample behaves as a near-critical gas condensate with a dew point pressure of 242 bar. The unusual shape of the Z-factor curve around 240 bar is due to the rapid change in equilibrium gas composition just below dew point pressure.

Figure 40, Figure 41 and Figure 42 show the corresponding results for four 'decontaminated' fluids based on a sample with 20% contamination. Fluid 4 was calculated with the spreadsheet using the 'skimming' method, and Fluid 5 with the 'subtraction' method. Fluids 6 and 7 were calculated with PhazeComp, assuming an exponential distribution, with Fluid 6 derived from a fit to component amounts and Fluid 7 derived from a fit to molecular weight boundaries. Table 18 compares the calculated dew point pressures and oil-gas ratios. Fluids 5 and 7 give the best fit to the data for the original reservoir fluid, but the discrepancies for the other two fluids are still relatively small in relation to other uncertainties in sampling and PVT measurements.

7.3 Discussion of Decontamination Results

The decontamination procedures used here were able to provide accurate estimates of the reservoir fluid composition from contaminated sample compositions. PVT calculations on the 'decontaminated' fluid compositions gave practically the same results as for the original fluid composition.

The 'skimming' method gave accurate results for samples contaminated with a 2-component OBM, but the 'subtraction' method – which requires knowledge of the OBM composition – was needed to give accurate results for the diesel OBM. When fitting the molar distribution to an analytic function, it appears preferable to use an error measure that assigns roughly equal importance to each component.

The results of calculations using the spreadsheet model (in Table 11 to Table 14) show that the accuracy of the decontaminated fluid composition is not very sensitive to the level of contamination. The accuracy depends far more on how well the molar distribution fits the analytical model being used. However, when PVT measurements on contaminated samples are used to calibrate an EoS model, the contamination should be minimised so that the experimental data are as representative as possible of the reservoir fluid.

The assessment of decontamination procedures is based mainly on calculations with the SPE3 fluid, although the conclusions are consistent with results in References 5 and 10. Further calculations with a wider range of reservoir fluids are needed to confirm these results.

8 Conclusions

1. The most important parameters in determining the OBM contamination levels are the level of OBM penetration during drilling, the cumulative production during clean-up and the k_v/k_h ratio. Other parameters, such as heterogeneity, drawdown, the flow area to the well, and the relative permeability are less important.
2. Contamination levels are higher for leaner fluids, but only because of the definition of contamination as a weight fraction of the dead condensate. The OBM mol fraction in the wellstream does not vary greatly with reservoir fluid.
3. Contamination with OBM may either raise or lower the dew point pressure of gas condensate fluids, but the direction of the dew point change does not appear to have a significant effect on contamination levels.
4. When extrapolating the OBM contamination levels in time, the best method appears to be a log-log plot of OBM mol fraction versus time.
5. It is still possible to obtain accurate samples even when the flowing bottom hole pressure is below the dew point pressure, provided that the well has flowed for long enough for the condensate bank to stabilize.
6. Large rate changes should be avoided prior to sampling, even when the flowing bottom hole pressure is below the dew point. Reductions in the production rate lead to 'unloading' of the condensate bank, increasing the concentration of liquid components in the wellstream.
7. The presence of OBM does not appear to have any major impact on the composition of the decontaminated sample. If a suitable method is available for 'removing' the OBM components from the sample, then there appears to be no significant difference in the sample from wells with and without OBM contamination.
8. Decontamination procedures were developed by fitting the molar distribution to exponential or gamma functions, using both an Excel spreadsheet and PVT software. These procedures were able to provide accurate estimates of the reservoir fluid composition from contaminated sample compositions. PVT calculations on the 'decontaminated' fluid compositions gave practically the same results as for the original fluid composition.

9 References

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10 Appendices

10.1 Example Sensor data set

```

TITLE
*Al.dat

  OBM Gas Condensate Project.

  Grid with 10 cm OBM zone, 4 cells in r direction in OBM zone
  Also refined in z direction near well, with 3 completions

  SPE 3 gas condensate fluid system. 22 components + 2 extra OBM components
  Start at Pdew + 10 psi
  10 md reservoir, kv/kh=1
  IMPES solution with CFL=2 and no wellbore crossflow

  OBM at start in first 4 cells (10 cm)
  Production rate 60 l/hr rate for full well through sampling tool

ENDTITLE

GRID  24 8 31

CPU

CPULIM 400

PSM          ! Needed for generation of PSM file containing molar streams

MAPSPRINT 1  P PSAT SW SO SG DEPTH  PV

C   Bwi  cw      denw  visw   cr      pref
MISC 1    3E-6   62.4  0.5   4.E-6   6000

C -----
C  define radial grid
C  use total dtheta = 180 deg
C -----

RADIAL
3
0.3750 1000

  0.375  0.478  0.564  0.639  0.703  0.762
  0.818  0.916
  1.015  1.113  1.212  1.310  1.408
  1.507  1.622  1.786
  2.114  2.77  4.1  6.7
  13.498 26.622 92.239 354.706

12.5  14.5  17  20  23  27  31  35

C -----
C  fine grid with DZ = 1.6 cm near to well completion
C -----

THICKNESS ZVAR
6.56  3.28  1.64  0.98  0.66
0.33  0.16  0.16  0.16  0.16
0.16  0.16
0.08  0.08  0.053  0.054  0.053  0.08  0.08
0.16  0.16  0.16  0.16  0.16
0.16  0.33  0.66  0.98  1.64
3.28  6.56

C -----
C  Rock rel perm curves
C -----

```

KRANALYTICAL 1
 .2 .2 .2 0.05 ! Swc Sorw Sorg Sgc
 .5 .7 1. ! krw(Sorw) krg(Swc) kro(Swc)
 2 2 2 2 ! nw now ng nog

ROCKTYPE CON
 1

REGION CON
 1

KX CON
 10
 KY EQUALS KX
 KZ EQUALS KX

POROS CON
 0.2

DEPTH CON
 10000

C -----
 C PVT data for SPE3, 22 components + 2 component OBM
 C -----

PVTEOS SRK
 200

CPT	MW	TC	PC	AC	SHIFT	ZCRIT
C1N2	16.385	339.45	662.08	0.01169	-0.00243	0.28635
C2C02	31.773	548.01	735.34	0.11077	0.07225	0.27883
C3	44.097	665.69	616.13	0.152	0.09075	0.2763
C4	58.123	750.86	540.12	0.19352	0.10993	0.27761
C5	72.15	835.77	489.76	0.23862	0.1069	0.27065
C6	83.42	922.10	476.95	0.2489	0.13432	0.26874
C7	96.858	984.77	443.08	0.27179	0.14154	0.26432
C8	110.623	1038.22	410.15	0.29236	0.14866	0.25987
C9	123.894	1085.29	379.15	0.31471	0.1638	0.25572
C10	137.118	1127.67	351.65	0.33686	0.17962	0.25192
C11	150.275	1166.16	327.35	0.35838	0.19556	0.24838
C12	163.355	1201.35	305.85	0.37907	0.21126	0.24503
C13	176.35	1233.73	286.78	0.39883	0.22652	0.24183
C14	189.255	1263.64	269.79	0.41762	0.24121	0.23873
C15	202.064	1291.40	292.70	0.50753	0.12451	0.23573
C16	214.775	1317.25	281.54	0.53575	0.12467	0.23281
C17	227.385	1341.42	271.49	0.56348	0.12456	0.22997
C18	239.891	1364.08	262.41	0.59071	0.12415	0.22719
C19	252.293	1385.39	254.17	0.61742	0.12345	0.22448
C20-C23	278.291	1365.27	239.03	1.10642	0.06665	0.21895
C24-C29	332.813	1430.74	214.45	1.3822	0.05211	0.20804
C30+	421.003	1515.90	187.91	1.87923	0.02056	0.19247
C14-OBM	196.4	1240.20	226.26	0.644	0.28791	0.22956
C16-OBM	224.4	1290.60	192.90	0.721	0.33822	0.21749

BIN
 -0.00199 -0.00791 -0.01432 -0.02034 -0.02429 -0.02277 -0.0263 -0.02978
 -0.0331 -0.03626 -0.03924 -0.04204 -0.04467 -0.04203 -0.04371 -0.04526
 -0.04668 -0.04799 -0.0488 -0.05268 -0.05688 0 0
 22*0
 21*0
 20*0
 19*0
 18*0
 17*0
 16*0
 15*0
 14*0
 13*0
 12*0
 11*0
 10*0
 9*0

```

8*0
7*0
6*0
5*0
4*0
3*0
2*0
0

C -----
C Initialization region 1 is the inner 10 cm (OBM)
C Initialization region 2 is the rest of the model (reservoir fluid)
C -----

INITREG XVAR
1 1 1 1 23*2

INITIAL 1 ! OBM (add a little C1 to get Psat so Sensor calls this a liquid!)
  DEPTH ! PSATDP  ZI
    10000  100.0  0.001  21*0  0.6893  0.3097

  PINIT  3377
  ZINIT  10017

INITIAL 2 ! SPE 3 Reservoir fluid
  DEPTH ! PSATDP  ZI
    1000  3550  0.67730  0.09870  0.05893  0.05155  0.02682  0.01861  0.01482  0.01541
          0.01082  0.00754  0.00507  0.00353  0.00271  0.00209  0.00136  0.00115
          0.00084  0.00063  0.00053  0.00106  0.00043  0.00011  2*0

  PINIT  3377
  ZINIT  10017

ENDINIT

C -----
C Print out controls
C -----

MAPSFREQ 1

DSMAX 0.1 !
DXMAX 0.2 !

c PRINTZERO 1

WINDOWS
1 1 20 1 1 1 27 XZY
2 1 20 1 1 1 27 XYZ

MAPSPRINT OFF
MAPSPRINT 1 P SO PSAT

C print OBM mole fractions in window 2

MAPSPRINT 2 X Y

MAPSX 2 23 24
MAPSY 2 23 24

STEPFREQ 1
WELLFREQ 1
MAPSFREQ 1
SUMFREQ 100 ! print timestep summaries every 10 timesteps

C -----
C Define 'production well' completed in centre, theta=1
C -----

WELL
      I  J  K1 K2  RW
PROD  1  1  15 17  0.375

```

```

BHP
  PROD 750

WELLTYPE
  PROD RBTOT

RATE
  PROD 4.5 ! corresponds to 9 rb/d for full well ( = 1 l/min or 0.25 gal/min)

WELLCROSS
  PROD 0 ! no crossflow

C -----
C timestep data
C -----

DT .0005 ! initial timestep

CFL 1 ! tighter CFL for first period after production starts

TIME 0.01

CFL 2 ! slacken CFL limit

TIME 0.042 ! 1 hour production
TIME 0.083 ! 2 hour production
TIME 0.125 ! 3 hour production
TIME 0.167 ! 4 hour production
TIME 0.208 ! 5 hour production

MAPSFILE P SO PSAT X Y
MAPSFILEFREQ 1

TIME 0.25 ! 6 hour production

END

```

10.2 Example PhazeComp decontamination data set

```

-----
-- OBM Gas Condensate Project
-- Decontamination of Wellstream Compositions from
-- Sensor simulations with 2 component OBM
-- R E Mott May 2003
-----

-- TWUMNW 0 gives n-paraffin Molecular weights
-- gives MW intervals of 14, thought to be consistent with practice of PVT labs

TWUMW 0

-----
-- define fluid characterization as in the simulator with 2 extra OBM components
-----

CHARACTERIZATION "24comp_Simulation_Model"

Component      MW      LMW
C1N2
C2CO2
C3
C4
C5
C6
C7
C8
C9
C10

```

C11
 C12
 C13
 C14P
 C15
 C16P
 C17
 C18
 C19
 C20-24
 C25-29
 C30+
 OBM1
 OBM2

LUMP C7+ C7 16*1
 LUMP C14 C14P OBM1
 LUMP C16 C16P OBM2

 -- Read in wellstream 'SAMPLE2' from simulator with obm components at end.
 -- Sample from Run ALG2 at 20% contamination

MIX SAMPLE2 MOLES ; 20% contamination

0.67031 0.09761 0.05825 0.05093 0.02648 0.01836 0.01461 0.01519 0.01066 0.00742
 0.00499 0.00347 0.00266 0.00205 0.00133 0.00113 0.00082 0.00062 0.00052 0.00103
 0.00041 0.00010 0.00762 0.00342

 -- define characterization without OBM components

-- Fluid chracterization without separate OBM components
 -- C14P and OBM1 are now combined as C14
 -- C16P and OBM2 are now combined as C16

CHARACTERIZATION "22comps_without_OBM"

Component	MW	LMW
C1N2		
C2CO2		
C3		
C4		
C5		
C6		
C7		
C8		
C9		
C10		
C11		
C12		
C13		
C14		
C15		
C16		
C17		
C18		
C19		
C20-24		
C25-29		
C30+		

LUMP C7+ C7 16*1

MIX SAMPLE SAMPLE2 ; convert sample to the 22 comp characterization

 -- define characterization with properties of the 2 OBM components

CHARACTERIZATION "OBM_2C"

Component	MW	Tc(K)	Pc(bar)	AF	VT	Tb(K)	SG
-----------	----	-------	---------	----	----	-------	----

```

-----
      OBM1      196.400      689.000      15.6000      0.644      0.19085      524.286      0.775
      OBM2      224.400      717.000      13.3000      0.721      0.24874      558.243      0.785

LUMP OBM OBM1 OBM2
LUMP C14 OBM1
LUMP C16 OBM2

MIX OB_MUD MOLES ; define the OBM composition
0.69 0.31

MIX OB_MUD 1 mole OB_MUD ; normalize

-----
-- go back to the characterization with no separate OBM components
-----

RESTORE "22comps_without_OBM"

-----
-- Calculate the estimate of uncontaminated reservoir fluid by subtracting out an
-- estimated (f) amount of obm contaminant.
-----

VARIABLE f 0.0 0.014 ; the maximum (0.14) is set to avoid negative amounts

MULTIPLY Moles of C1N2 to C30+ in OB_MUD by f

MIX DECON 1 tank SAMPLE -1 tank OB_MUD ; calc decontaminated sample composition
MIX DECON 1 mole DECON ; normalize decontaminated sample composition

-----
-- Gamma fit the DECON mixture.
-- Carry residuals from Gamma fit to global regression for the OBM amount.
-----

Gamma
  Average 130 250 ; range of values for average MW
  Shape 1 0.5 2 ; Initial estimate and range of values for Shape factor
  Bound 90 85 100 ; Initial estimate and range of values for average MW

  Fit DECON C7 Amount ; fit the C7+ molar distribution in decontaminated sample
  Ignore C20-24 ; ignore the C20+ fraction

End

EOF

```

11 Tables

Table 1. SPE3 fluid compositions (mol per cent).

	SPE3 (Original fluid)	SPE3L (Lean fluid)
C1N2	67.730	73.409
C2CO2	9.870	9.609
C3	5.893	5.287
C4	5.155	4.318
C5	2.682	2.083
C6	1.861	1.337
C7	1.482	0.998
C8	1.541	0.978
C9	1.082	0.649
C10	0.754	0.429
C11	0.507	0.274
C12	0.353	0.182
C13	0.271	0.133
C14	0.209	0.098
C15	0.136	0.058
C16	0.115	0.047
C17	0.084	0.033
C18	0.063	0.023
C19	0.053	0.019
C20-C23	0.106	0.028
C24-C29	0.043	0.008
C30+	0.011	0.001

Table 2. SPE3 EoS Model Parameters

	Molecular weight	Tc (K)	Pc (bar)	Acentric factor	Volume shift		Binary interaction parameter with C1N2
C1N2	16.385	188.58	45.648	0.0117	-0.0024		
C2CO2	31.773	304.45	50.699	0.1108	0.0723		-0.00199
C3	44.097	369.83	42.480	0.1520	0.0908		-0.00791
C4	58.123	417.14	37.239	0.1935	0.1099		-0.01432
C5	72.150	464.32	33.767	0.2386	0.1069		-0.02034
C6	83.420	512.28	32.884	0.2489	0.1343		-0.02429
C7	96.858	547.10	30.549	0.2718	0.1415		-0.02277
C8	110.623	576.79	28.278	0.2924	0.1487		-0.02630
C9	123.894	602.94	26.141	0.3147	0.1638		-0.02978
C10	137.118	626.48	24.245	0.3369	0.1796		-0.03310
C11	150.275	647.87	22.569	0.3584	0.1956		-0.03626
C12	163.355	667.42	21.088	0.3791	0.2113		-0.03924
C13	176.350	685.40	19.772	0.3988	0.2265		-0.04204
C14	189.255	702.02	18.601	0.4176	0.2412		-0.04467
C15	202.064	717.44	20.180	0.5075	0.1245		-0.04203
C16	214.775	731.81	19.411	0.5358	0.1247		-0.04371
C17	227.385	745.23	18.718	0.5635	0.1246		-0.04526
C18	239.891	757.82	18.092	0.5907	0.1242		-0.04668
C19	252.293	769.66	17.524	0.6174	0.1235		-0.04799
C20-C23	278.291	758.48	16.481	1.1064	0.0667		-0.04880
C24-C29	332.813	794.86	14.786	1.3822	0.0521		-0.05268
C30+	421.003	842.17	12.956	1.8792	0.0206		-0.05688
C14-OBM	196.400	689.00	15.600	0.6440	0.2879		0.00000
C16-OBM	224.400	717.00	13.300	0.7210	0.3382		0.00000

All other binary interaction parameters are zero.

Table 3. NS-1 fluid compositions (mol per cent).

	NS-1 (original fluid)	NS-1M (medium rich fluid)	NS-1L (lean fluid)
C1N2	73.500	77.038	80.437
C2CO2	10.170	10.095	9.807
C3	3.550	3.354	3.071
C4	2.160	1.964	1.707
C5	1.320	1.153	0.950
C6	1.090	0.910	0.709
C7	1.081	0.874	0.651
C8	0.951	0.746	0.531
C9	0.807	0.613	0.417
C10	0.698	0.514	0.335
C11	0.604	0.431	0.269
C12	0.523	0.362	0.217
C13	0.452	0.304	0.174
C14	0.392	0.256	0.140
C15	0.340	0.215	0.113
C16	0.295	0.181	0.091
C17	0.256	0.152	0.073
C18	0.223	0.128	0.059
C19	0.194	0.108	0.048
C20-24	0.654	0.335	0.132
C25-29	0.337	0.147	0.046
C30+	0.405	0.120	0.023

Table 4. NS-1 EoS Model Parameters

	Molecular weight	Tc (K)	Pc (bar)	Acentric factor	Volume shift		Binary interaction parameter with C1N2	Binary interaction parameter with C2CO2
C1N2	16.093	190.25	45.935	0.0111	-0.1500			-0.00018
C2CO2	33.319	295.58	51.249	0.1127	-0.0520		-0.00018	
C3	44.097	369.83	42.480	0.1520	-0.0638		0.00018	0.00397
C4	58.123	419.45	37.448	0.1954	-0.0566		0.00021	0.00195
C5	72.150	465.24	33.756	0.2409	-0.0423		0.00021	0.00195
C6	83.079	512.67	33.192	0.2466	-0.0023		0.00021	0.00195
C7	96.477	545.68	31.109	0.2866	-0.0039		-0.01401	0.00195
C8	109.837	572.04	29.312	0.3317	-0.0168		-0.01645	0.00195
C9	123.152	596.15	27.537	0.3806	-0.0204		-0.01897	0.00195
C10	136.273	617.60	25.978	0.4295	-0.0225		-0.02138	0.00195
C11	149.321	637.08	24.600	0.4786	-0.0236		-0.02369	0.00195
C12	162.286	654.89	23.381	0.5229	-0.0242		-0.02590	0.00195
C13	175.161	671.27	22.298	0.5696	-0.0246		-0.02800	0.00195
C14	187.942	686.41	21.334	0.6160	-0.0250		-0.03000	0.00195
C15	200.623	700.45	20.472	0.6620	-0.0255		-0.03189	0.00195
C16	213.203	713.53	19.698	0.7077	-0.0261		-0.03368	0.00195
C17	225.678	725.76	19.001	0.7530	-0.0270		-0.03537	0.00195
C18	238.047	737.22	18.371	0.7980	-0.0281		-0.03697	0.00195
C19	250.308	748.00	17.799	0.8427	-0.0296		-0.03848	0.00195
C20-C24	283.140	774.39	16.486	0.9623	-0.0349		-0.04217	0.00195
C25-C29	341.526	814.29	14.738	1.1751	-0.0497		-0.04765	0.00195
C30+	466.791	879.96	12.452	1.6265	-0.0995		-0.05592	0.00195
C14-OBM	196.400	689.00	15.600	0.6440	0.1909		0.00000	0.00000
C16-OBM	224.400	717.00	13.300	0.7210	0.2487		0.00000	0.00000

All other binary interaction parameters are zero.

Table 5. Summary of reservoir fluid properties

	SPE3	SPE3L	NS-1	NS-1M	NS-1L
C7+ fraction (mol %)	6.81	3.96	8.21	5.49	3.32
Dew point pressure (bar a)	232	222	466	428	364
OGR (stock tank m3/MM std m3)	746	381	965	556	286

Note. OGR calculated from 3 stage separation at 70 bar(a) / 68 deg C, 18 bar(a) / 27 deg C, 1.03 bar(a) / 15.5 deg C.

Table 6. Diesel OBM compositions (mol per cent).

C11	0.026
C12	1.392
C13	8.681
C14	19.300
C15	23.774
C16	20.166
C17	13.288
C18	7.316
C19	3.529
C20	2.528

Table 7. Cell dimensions for base case simulation grid

Cell no	dr (cm)	dtheta	dz (cm)
1	3.1	12.5	200
2	2.6	14.5	100
3	2.3	17	50
4	2.0	20	30
5	1.8	23	20
6	1.7	27	10
7	3	31	5
8	3	35	5
9	3		5
10	3		5
11	3		5
12	3		5
13	3		2.4
14	3.5		2.4
15	5		1.6
16	10		1.6
17	20		1.6
18	40		2.4
19	80		2.4
20	200		5
21	400		5
22	2000		5
23	8000		5
24	20000		5
25			5
26			10
27			20
28			30
29			50
30			100
31			200

Note. Well is connected to cells (1,1,15), (1,1,16) and (1,1,17).

Table 8. Sensitivities studied in simulation Cases.

	Sensitivity	Base case				
		1	2	3	4	5
A	Reservoir Fluid	SPE 3	SPE3L	NS-1	NS-1M	NS-1L
B	Initial pressure	Dew point pressure + 0.7 bar	Dew point pressure + 7 bar			
C	OBM type	2 component OBM	Diesel OBM			
D	Grid	24x8x31, homogeneous	Random heterogeneities	Layered (complete in high perm)	Layered (complete in low perm)	Finer grid in θ and z. 24x14x61
E	Relative permeability	Rock curves	Straight lines			
F	Horizontal permeability	10 md	1 md			
G	k_v/k_h	1	0.1			
H	Production rate	1 litre/min	0.5 litre/min			
I	Clean-up time	6 hours	24 hours			
J	OBM volume	10 cm from well	13 cm from well	5 cm from well	No OBM	
K	How to introduce OBM	Fill blocks round well with 100% OBM	Via injection well			
L	Rate for sampling	No change of rate prior to sampling	Reduce rate to 0.1 l/m for 1 hour	Shut-in for 10 mins then reduce rate to 0.1 l/m for 1 hour	Reduction to 0.1 l/m over 1 hour in 3 steps.	Reduction to 0.1 l/m over 1 hour in 9 steps
M	Well connection	5 cm x 5 cm	10 cm x 10 cm			

Table 9. Simulation Cases.

Case	Case title	Description	Final OBM contamination (%)
1	A1	Base case, SPE3 fluid	10.3
2	A2	SPE 3L	16.5
3	A3	NS-1	6.7
4	A4	NS-1M	10.0
5	A5	NS1-L	17.2
6	A1C2	Diesel OBM, SPE3	12.8
7	A2C2	Diesel OBM, SPE 3L	21.2
8	A3C2	Diesel OBM, NS-1	8.5
9	A4C2	Diesel OBM, NS-1M	12.8
10	A5C2	Diesel OBM, NS-1L	21.4
11	A1B2	Undersaturated, SPE3	10.1
12	A2B2	Undersaturated, SPE3L	16.9
13	A3B2	Undersaturated, NS-1	6.6
14	A4B2	Undersaturated, NS-1M	9.9
15	A5B2	Undersaturated, NS-1L	17.1
16	A1F2	1md, SPE3	13.0
17	A2F2	1md, SPE 3L	18.1
18	A3F2	1md, NS-1	7.1
19	A4F2	1md, NS-1M	10.8
20	A5F2	1md, NS-1L	17.8
21	A1J2	OBM to 13.5 cm	14.1
22	A1J3	OBM to 5 cm	5.7
23	A1G2	kv/kh=0.1, SPE3	4.1
24	A3G2	kv/kh=0.1, NS-1	2.7
25	A1D3	2 x Higher perm in well layers	9.1
26	A1D4	2 x Lower perm in well layers	10.6
27	A1D2	Random variation in perm	10.4
28	A1E2	Straight line rel perms	10.7
29	A1K2	Introduce OBM by injection, SPE3	12.6
30	A3K2	Introduce OBM by injection, NS-1	7.8
31	A1M2	Larger flow area at well connection	10.4
32	A1H2	Run for 12 hours at half normal rate	9.8
33	A1I2	Run for 24 hours	3.2
34	A4D6F2	Fine grid	11.3
35	A1F2L2	Rate change before sampling	10.6
36	A1F2L3	Shut in and rate change before sampling	10.6
37	A1F2L4	Reduce rate in 3 steps before sampling	10.3
38	A1F2L5	Reduce rate in 9 steps before sampling	10.3
39	A1J4L2	No OBM, 10 md, rate reduction after 6 hrs	No OBM
40	A1F2J4L2	No OBM, 1 md, rate reduction after 6 hrs	No OBM

Table 10. C7+ mol fractions in decontaminated wellstream compositions after 6 hours clean-up.

	SPE3	SPE3L	NS-1	NS-1M	NS1-L
Base case (10 md, saturated)	6.81%	3.95%	8.21%	5.49%	3.32%
10 md, undersaturated	6.81%	3.95%	8.21%	5.49%	3.32%
1 md, saturated	6.74%	3.94%	8.14%	5.47%	3.31%
Reservoir fluid composition	6.81%	3.96%	8.21%	5.49%	3.32%

Table 11. Mol fractions in decontaminated wellstream compositions. SPE3 fluid, 2-component OBM, fit to exponential distribution with ‘skimming’ method.

	OBM contamination in sample					Reservoir fluid
	10%	20%	30%	40%	50%	
C14	0.211%	0.210%	0.208%	0.208%	0.206%	0.209%
C16	0.115%	0.115%	0.113%	0.113%	0.112%	0.115%
C7+	6.808%	6.783%	6.738%	6.739%	6.703%	6.811%

Table 12. Mol fractions in decontaminated wellstream compositions. SPE3 fluid, diesel OBM, fit to exponential distribution with ‘skimming’ method.

	OBM contamination in sample					Reservoir fluid
	10%	20%	30%	40%	50%	
C14	0.236%	0.236%	0.235%	0.235%	0.234%	0.209%
C15	0.177%	0.177%	0.177%	0.177%	0.176%	0.136%
C16	0.133%	0.133%	0.133%	0.133%	0.132%	0.115%
C7+	7.077%	7.077%	7.072%	7.056%	7.045%	6.811%

Table 13. Mol fractions in decontaminated wellstream compositions. SPE3 fluid, diesel OBM, fit to exponential distribution with ‘subtraction’ method.

	OBM contamination in sample					Reservoir fluid
	10%	20%	30%	40%	50%	
C14	0.224%	0.226%	0.224%	0.224%	0.224%	0.209%
C15	0.155%	0.156%	0.156%	0.155%	0.155%	0.136%
C16	0.132%	0.132%	0.131%	0.131%	0.131%	0.115%
C7+	6.878%	6.883%	6.873%	6.856%	6.847%	6.811%

Table 14. Mol fractions in decontaminated wellstream compositions. NS-1L fluid, diesel OBM, fit to exponential distribution.

	OBM contamination in sample				Reservoir fluid
	21%	30%	40%	50%	
C14	0.138%	0.138%	0.138%	0.138%	0.140%
C15	0.111%	0.111%	0.111%	0.110%	0.113%
C16	0.089%	0.089%	0.089%	0.088%	0.091%
C7+	3.319%	3.328%	3.338%	3.355%	3.320%

Table 15. Mol fractions in decontaminated wellstream compositions calculated with PhazeComp. SPE3 fluid at 20% contamination, 2-component OBM.

Distribution	exponential	exponential	gamma	gamma	Reservoir fluid
Fit	amounts	boundaries	amounts	boundaries	
C14	0.174%	0.270%	0.179%	0.257%	0.209%
C16	0.099%	0.142%	0.101%	0.136%	0.115%
C7+	6.720%	6.850%	6.727%	6.832%	6.811%

Table 16. Mol fractions in decontaminated wellstream compositions calculated with PhazeComp. SPE3 fluid at 20% contamination, diesel OBM.

Distribution	exponential	exponential	gamma	gamma	Reservoir fluid
Fit	amounts	boundaries	amounts	boundaries	
C14	0.181%	0.214%	0.180%	0.226%	0.209%
C15	0.101%	0.142%	0.100%	0.157%	0.136%
C16	0.085%	0.120%	0.084%	0.132%	0.115%
C7+	6.664%	6.827%	6.659%	6.884%	6.811%

Table 17. PVT properties of decontaminated samples calculated from SPE3 fluid with 20% contamination of 2-component OBM.

	Contaminated sample	Decontaminated compositions			Reservoir fluid
		Fluid 1 (spreadsheet, skimming)	Fluid 2 (PhazeComp, fit amounts)	Fluid 3 (PhazeComp, fit bounds)	
Saturation pressure (bar a)	237.9	231.3	231.4	231.5	232.4
OGR (stock tank m3/MM std m3)	905.1	741.1	734.4	753.5	745.6

Note. OGR calculated from 3 stage separation at 70 bar(a) / 68 deg C, 18 bar(a) / 27 deg C, 1.03 bar(a) / 15.5 deg C.

Table 18. PVT properties of decontaminated samples calculated from SPE3 fluid with 20% contamination of diesel OBM.

	Contaminated sample	Decontaminated compositions				Reservoir fluid
		Fluid 4 (spreadsheet, skimming)	Fluid 5 (spreadsheet, subtraction)	Fluid 6 (PhazeComp, fit amounts)	Fluid 7 (PhazeComp, fit bounds)	
Saturation pressure (bar a)	241.1	232.5	231.9	230.2	231.5	232.4
OGR (stock tank m3/MM std m3)	897.8	781.6	756.8	723.7	748.4	745.6

Note. OGR calculated from 3 stage separation at 70 bar(a) / 68 deg C, 18 bar(a) / 27 deg C, 1.03 bar(a) / 15.5 deg C.

12 Figures

Figure 1. C7+ mol fraction in gas phase during CVD – SPE3 fluids.

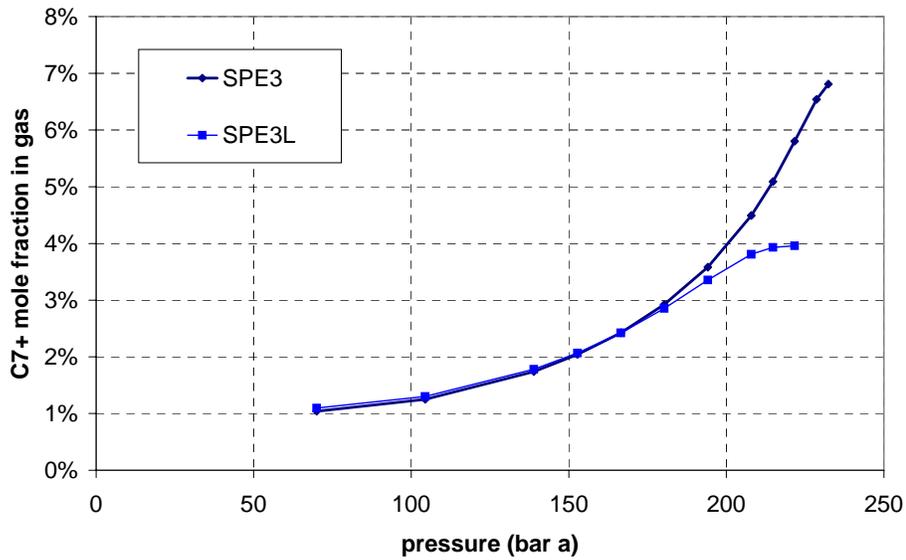


Figure 2. Liquid saturation during CVD – SPE3 fluids.

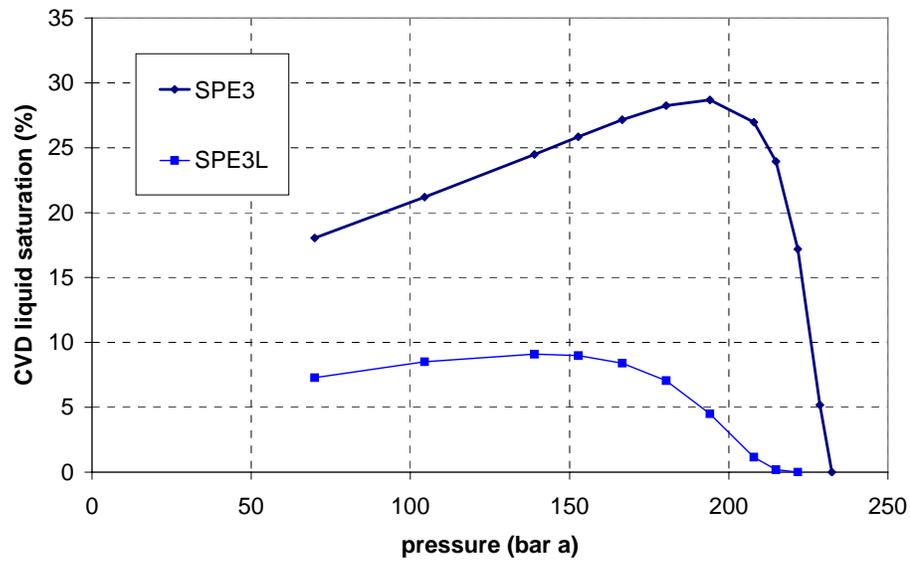


Figure 3. C7+ mol fraction in gas phase during CVD – NS-1 fluids.

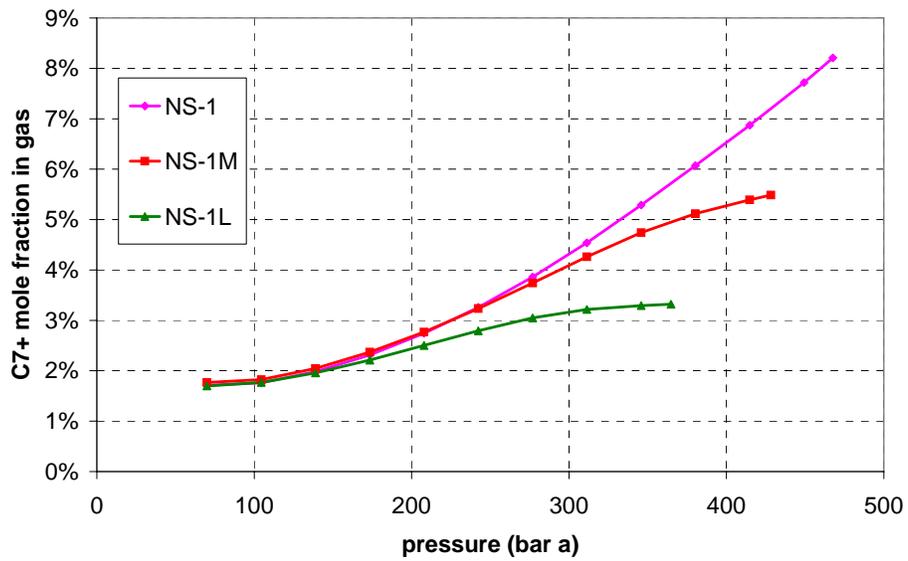


Figure 4. Liquid saturation during CVD – NS-1 fluids.

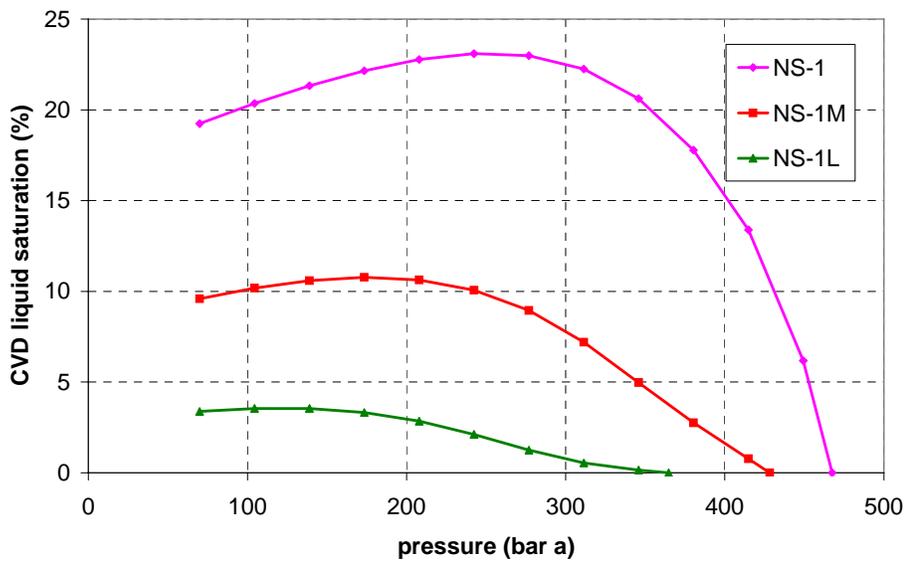


Figure 5. Saturation pressures for reservoir fluids contaminated with 2-component OBM

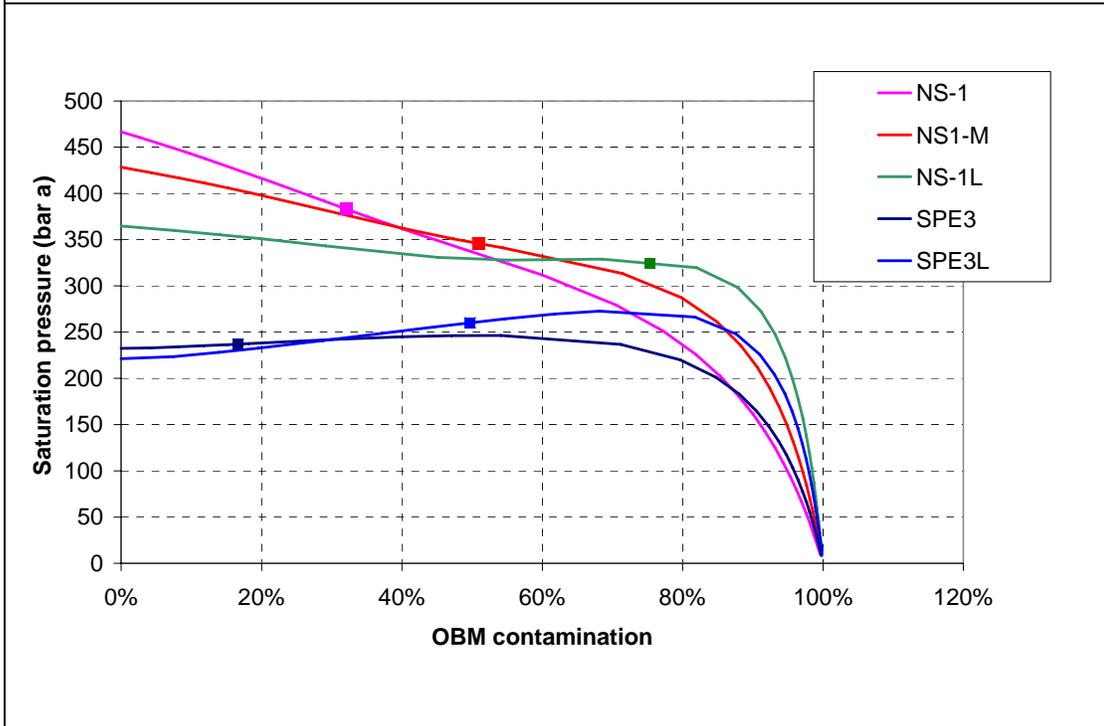


Figure 6. Saturation pressures for reservoir fluids contaminated with diesel OBM.

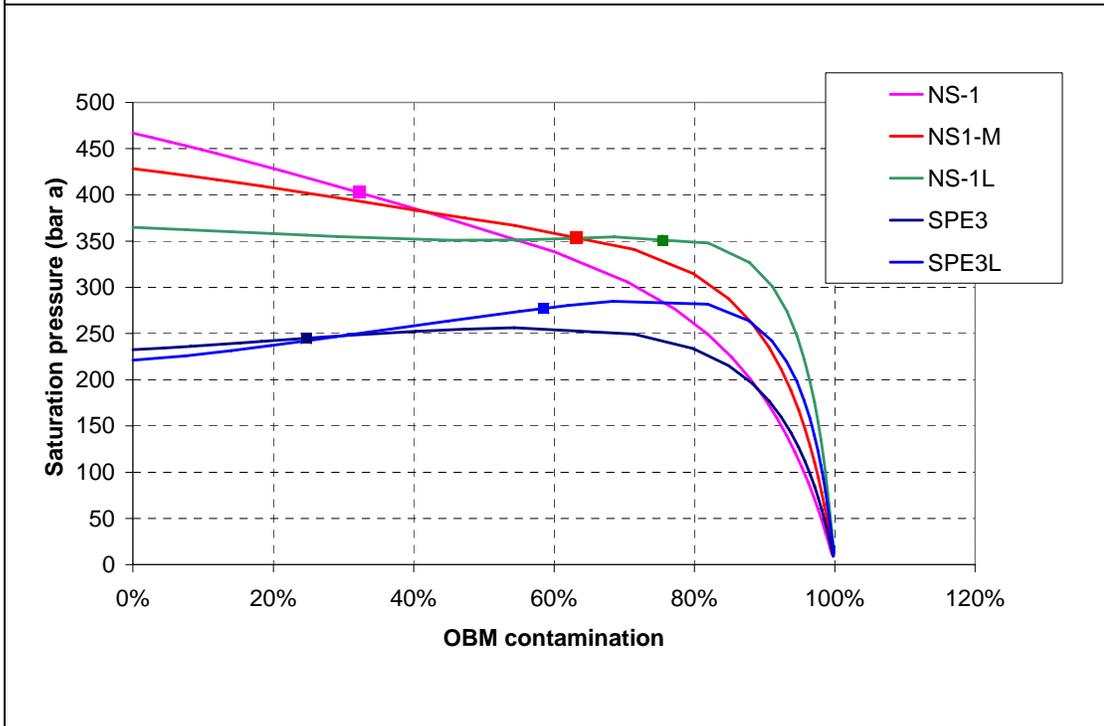


Figure 7. Saturation pressures for NS-1 equilibrium gases contaminated with 2-component OBM.

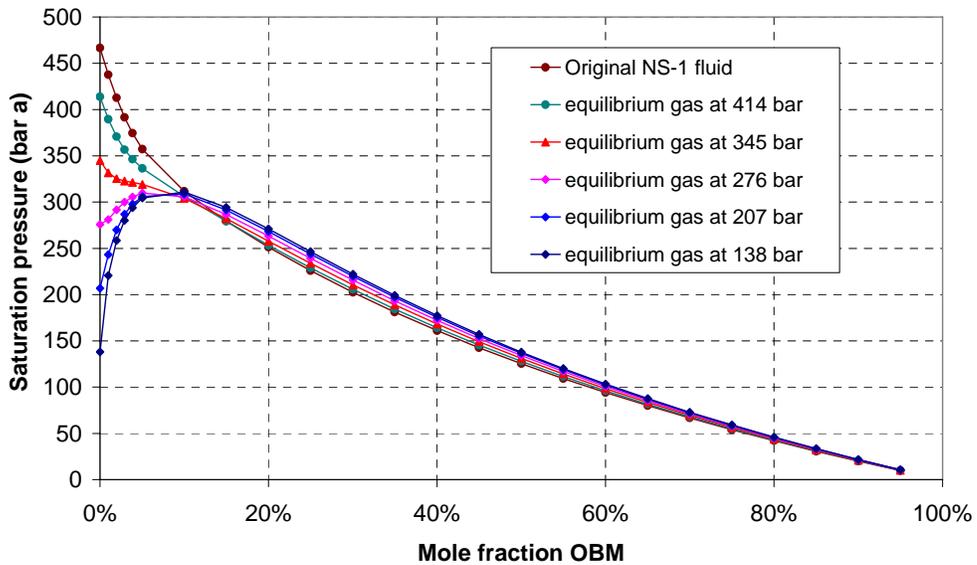
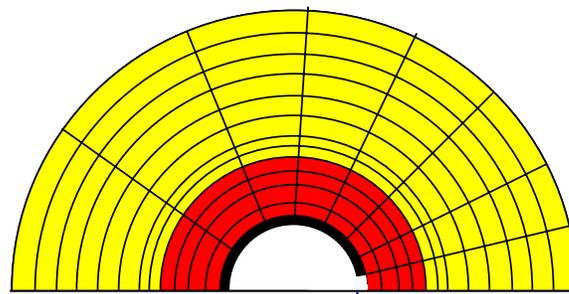


Figure 8. Central section of simulation grid in horizontal ($r-\theta$) plane. Red cells initially contain OBM. Yellow cells initially contain reservoir fluid.



Well connection to represent sampling tool

Figure 9. Map of central part of grid in vertical (x-z) plane through well completion. Colours show oil saturations in base case after 6 hours production.

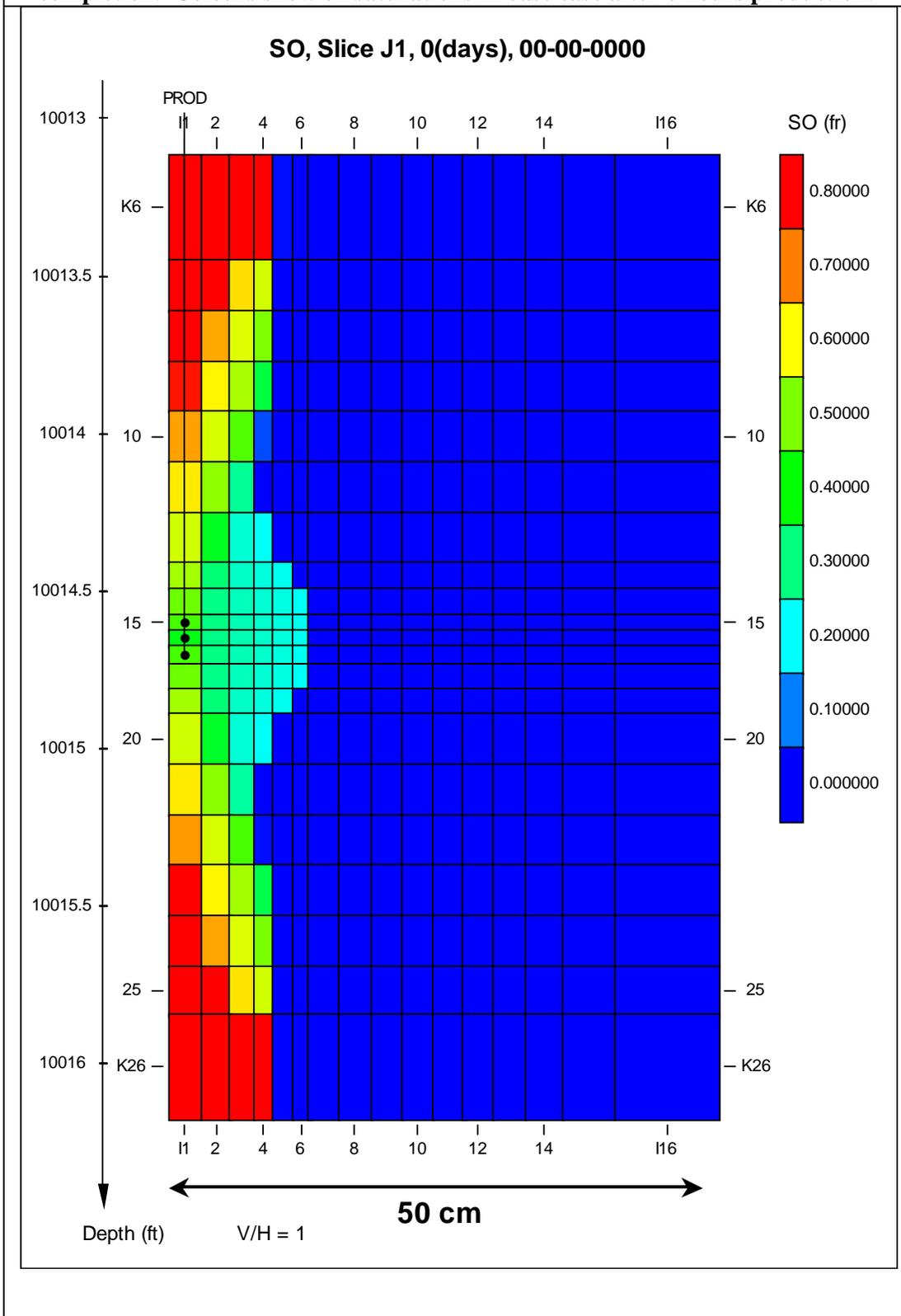


Figure 10. Initial OBM contamination for the two methods of initialising the simulation model.

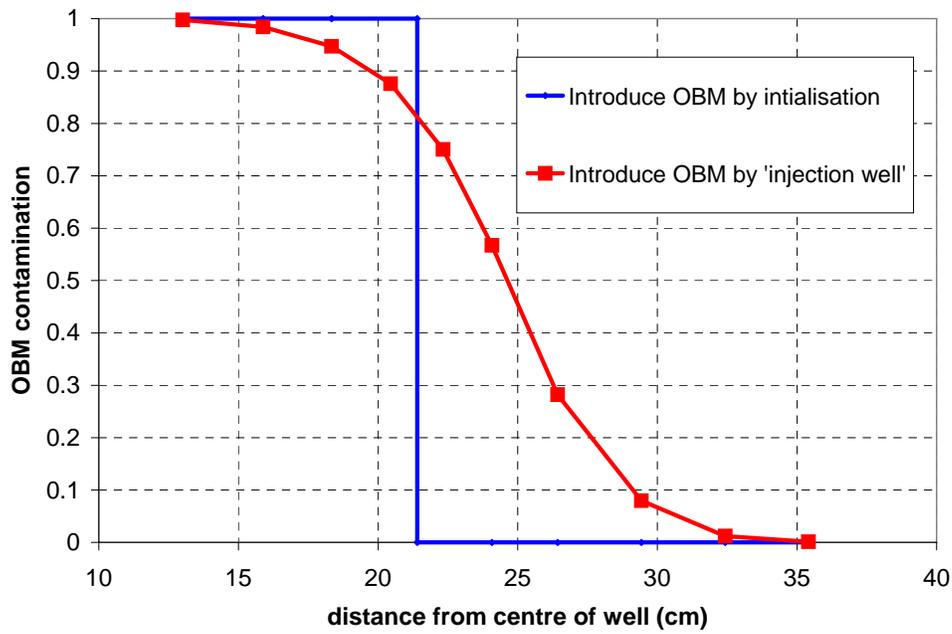


Figure 11. Reduction of OBM contamination with time during clean-up period.

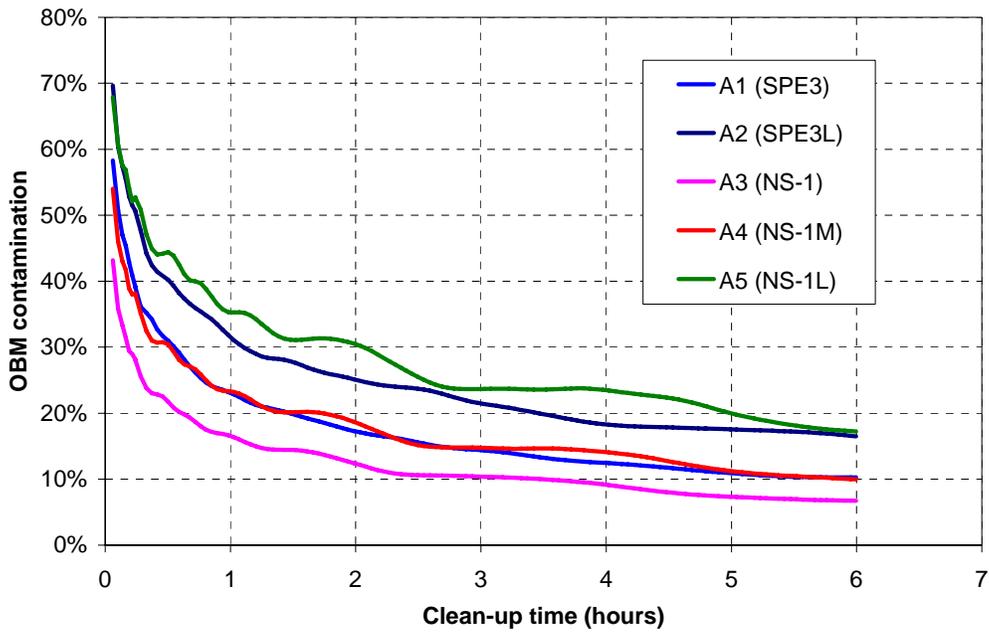


Figure 12. Effect of rate on reduction of OBM contamination during clean-up period.

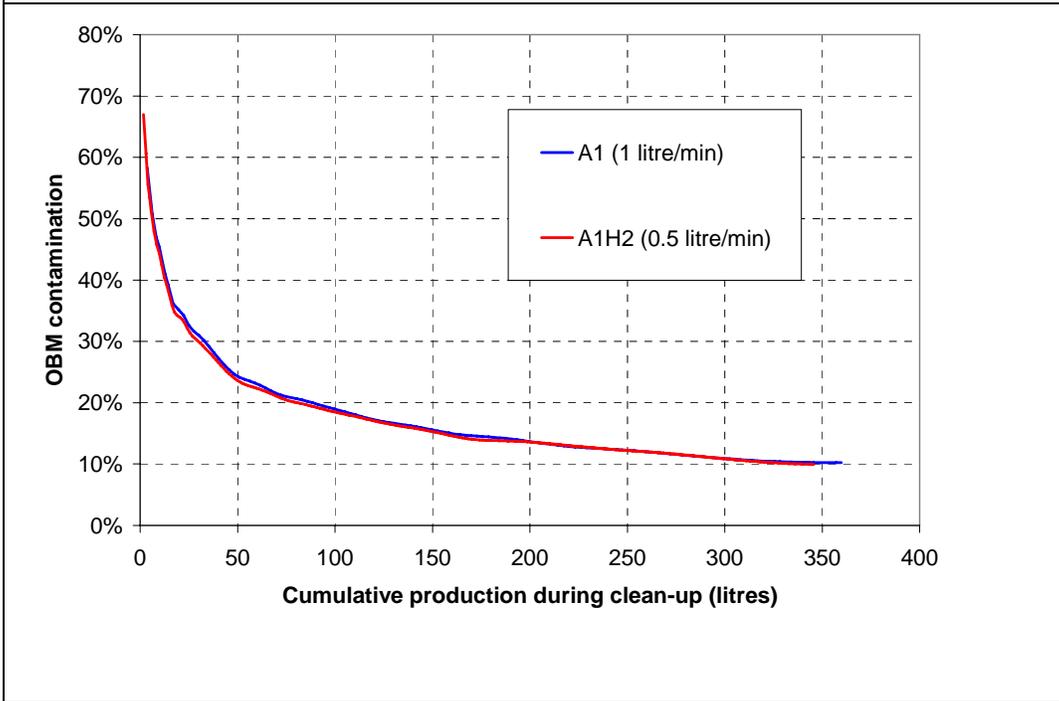
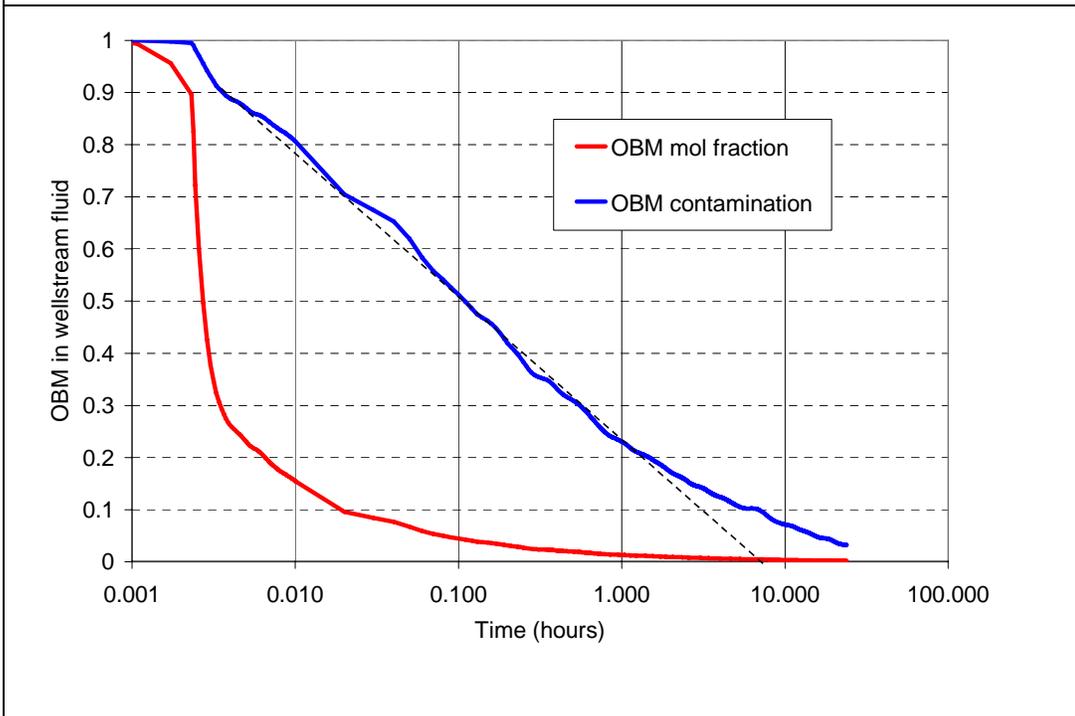


Figure 13. OBM mol fraction and contamination versus time for Case A1I2 (Base Case with 24 hours clean-up). Semilog plot.



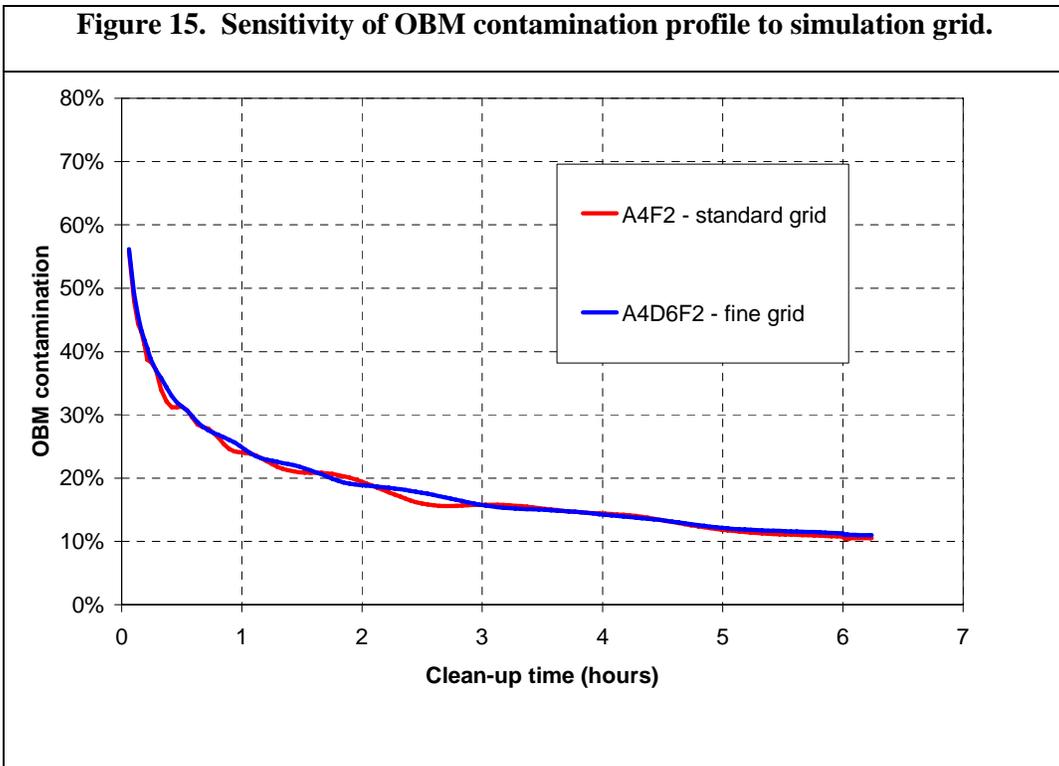
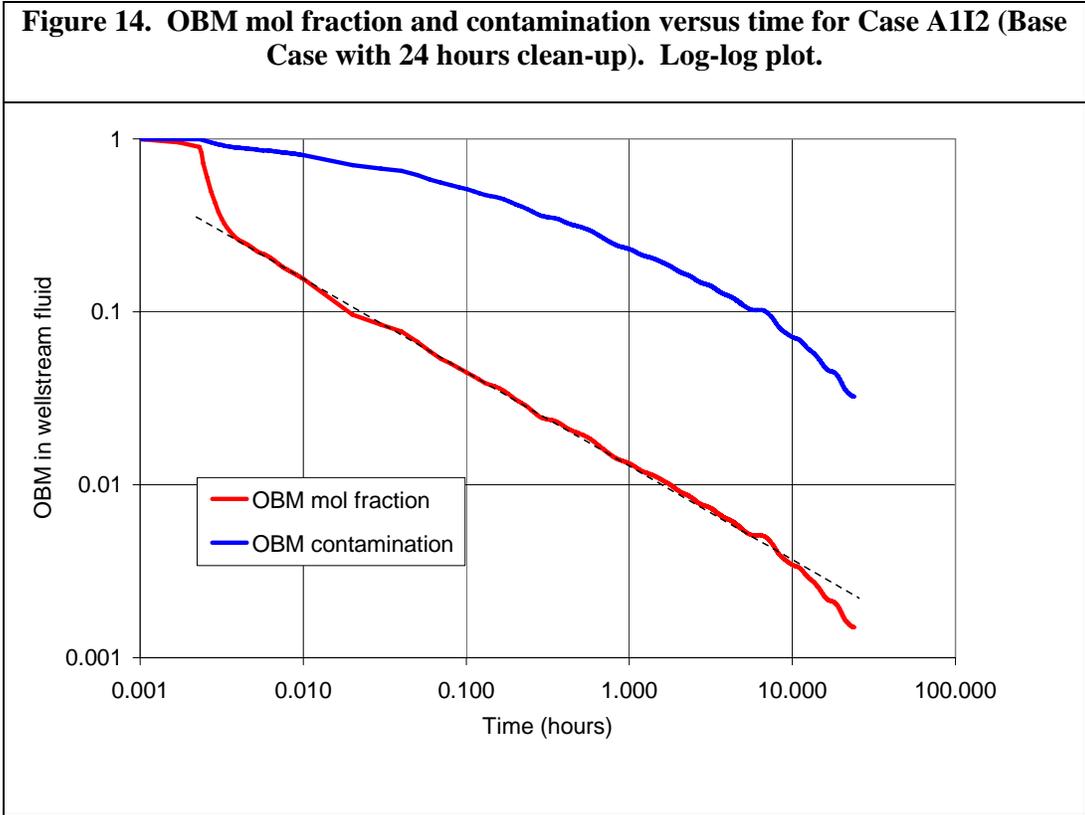


Figure 16. Oil saturation in vertical plane through well connection after 6 hours clean-up. SPE3 fluid, 10 md reservoir.

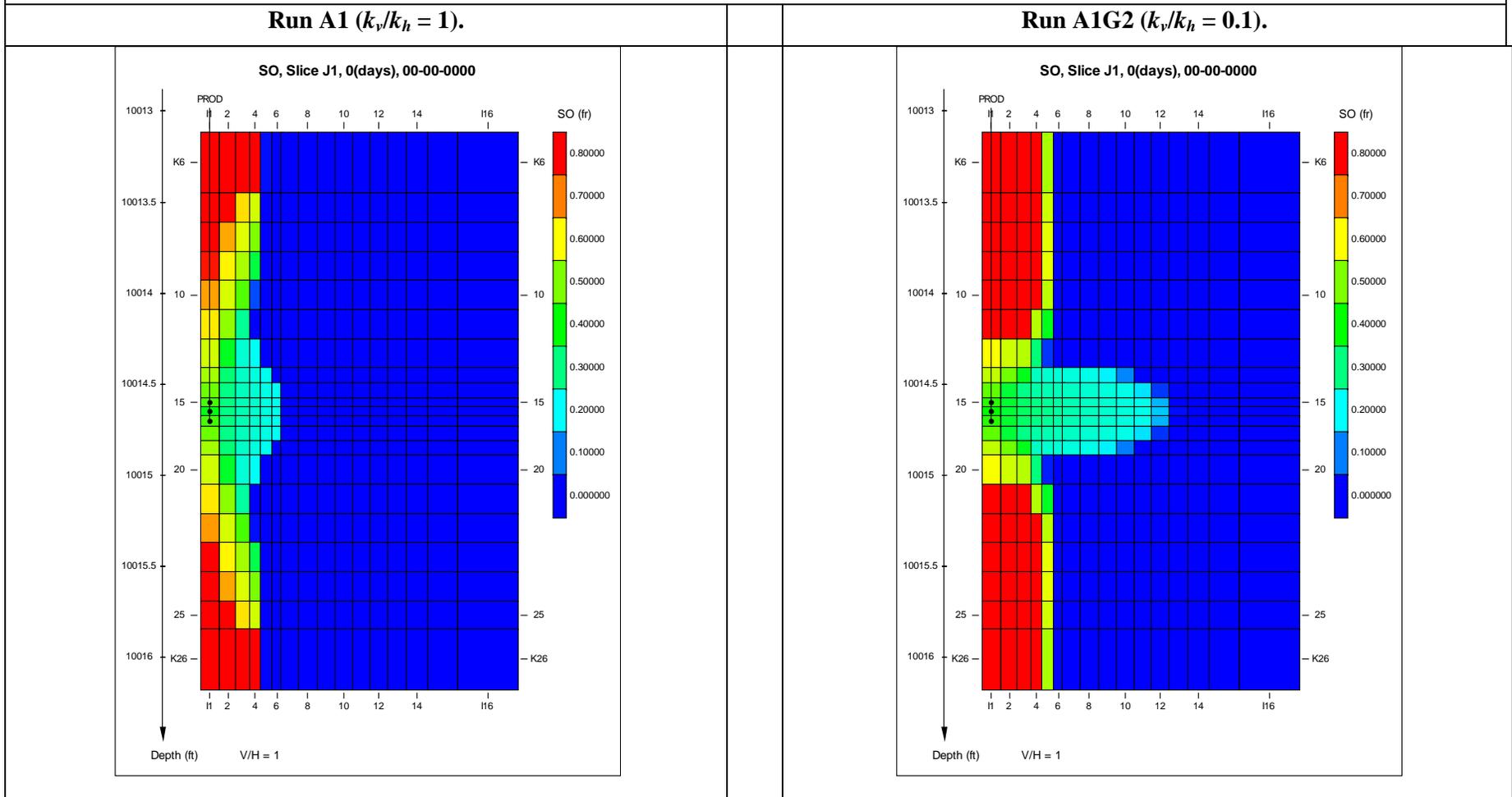


Figure 17. Oil saturation in vertical plane through well connection after 6 hours clean-up. SPE3 fluid, $k_v/k_h = 1$.

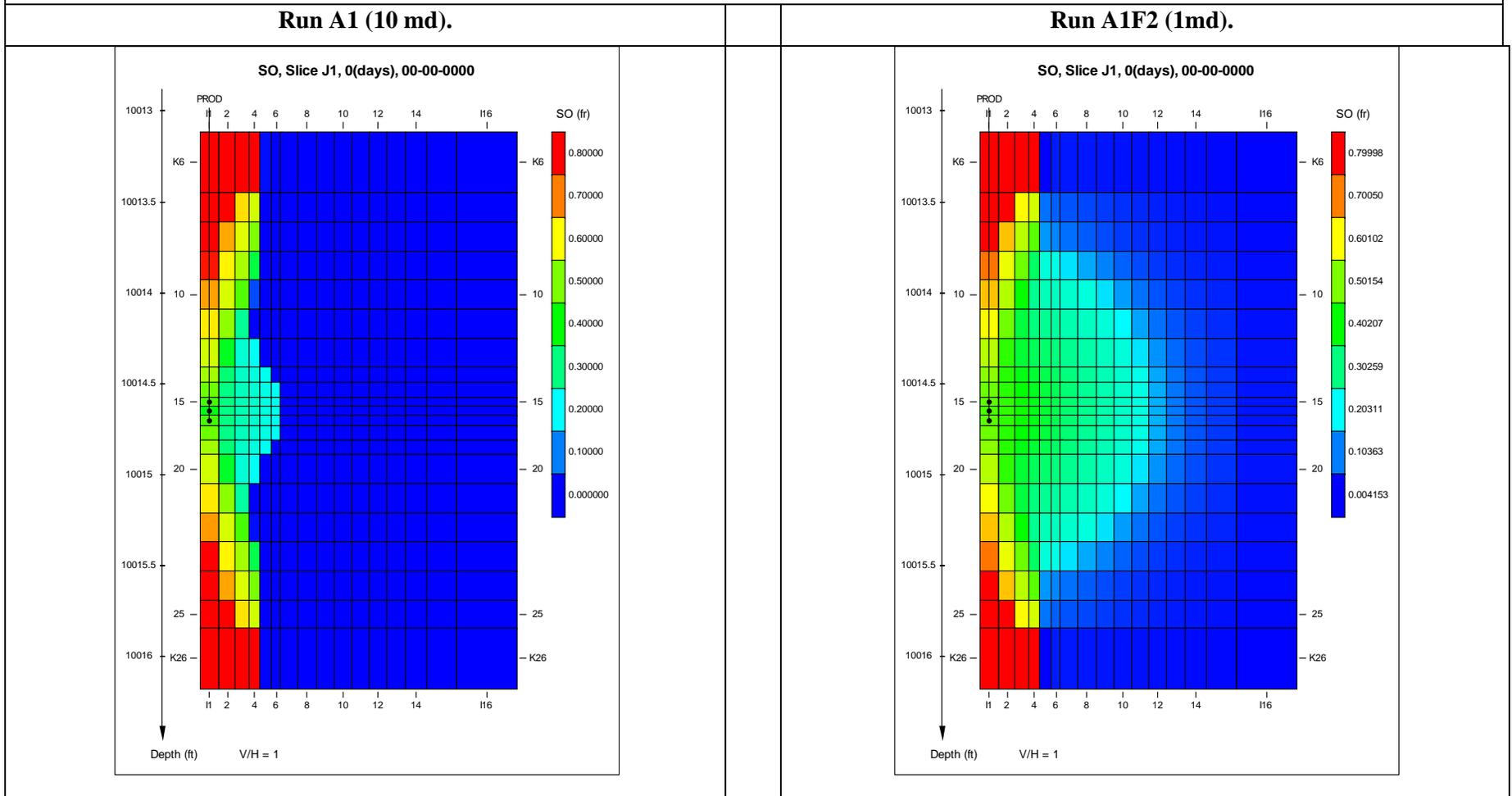


Figure 18. Oil saturation in vertical plane through well connection after 6 hours clean-up. NS-1 fluid, $k_v/k_h = 1$.

Run A3 (10 md).

Run A3F2 (1md).

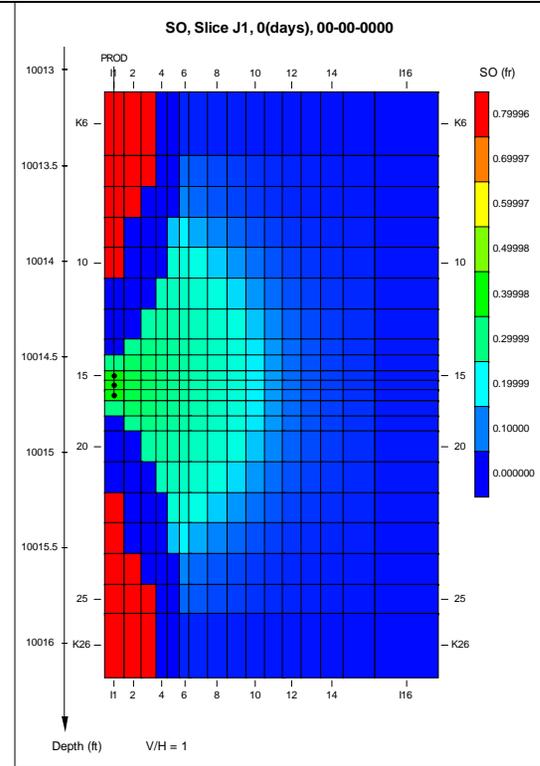
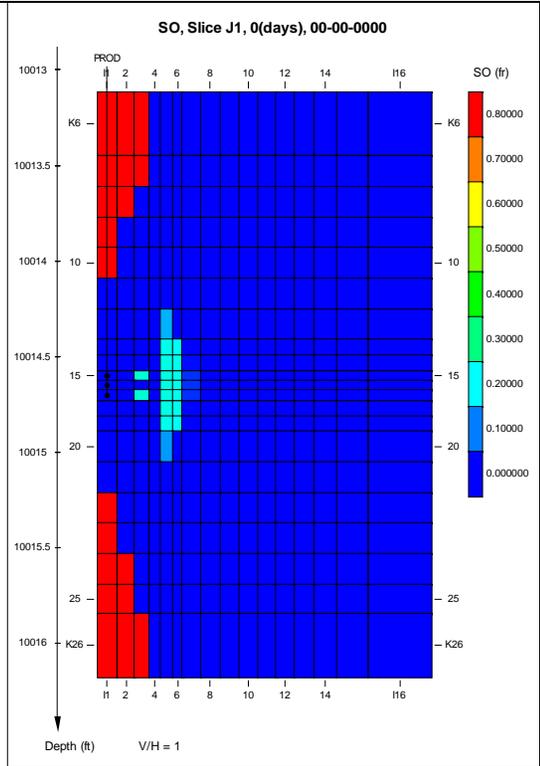


Figure 19. C7+ mol fraction in decontaminated wellstream fluid, with rate changes during sampling. SPE3 fluid.

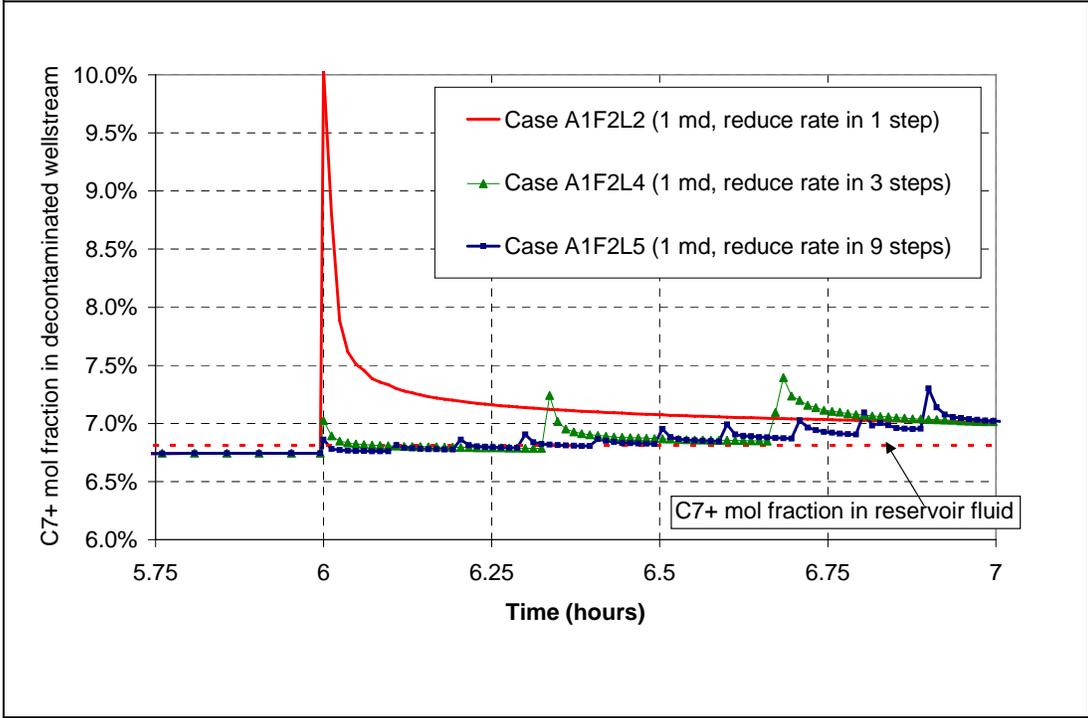


Figure 20. OBM mol fraction in wellstream fluid, with rate changes during sampling. SPE3 fluid.

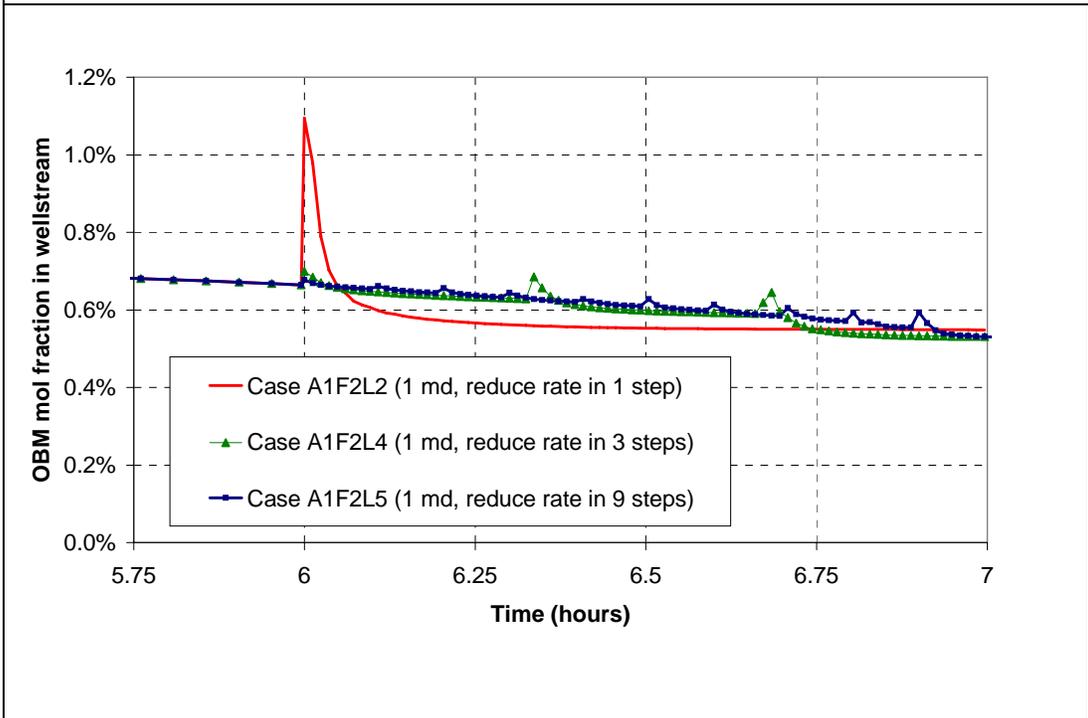


Figure 21. C7+ mol fraction in decontaminated wellstream fluid. SPE3 fluid, with and without OBM present.

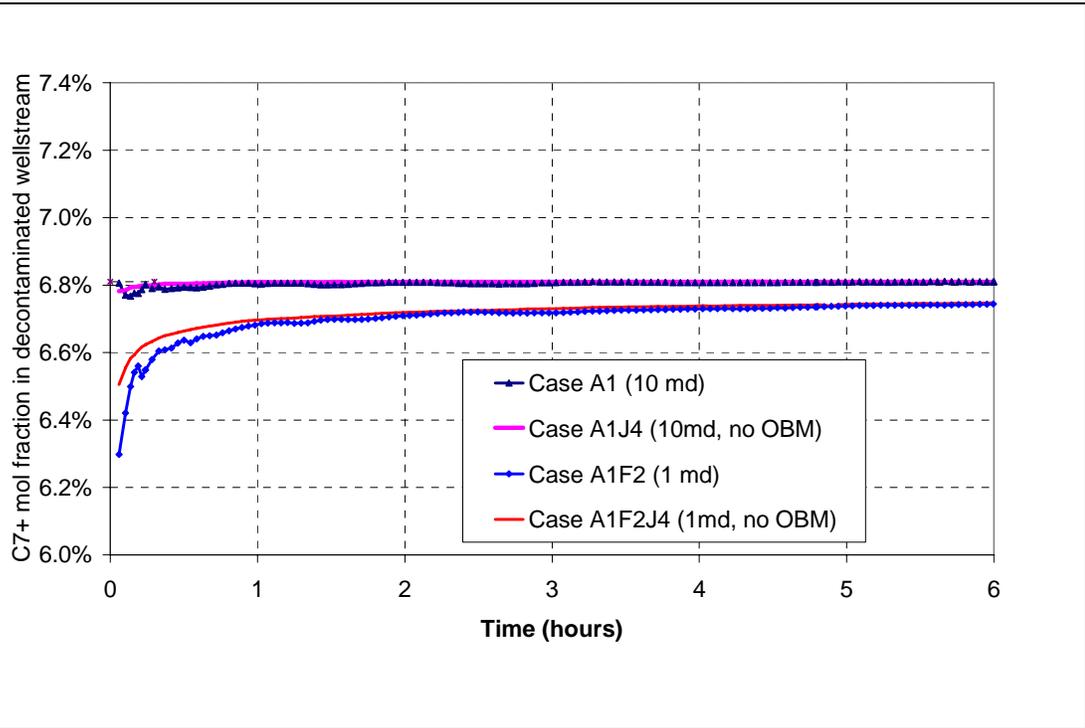


Figure 22. Molar distribution for contaminated wellstream samples. SPE3 fluid, 2-component OBM.

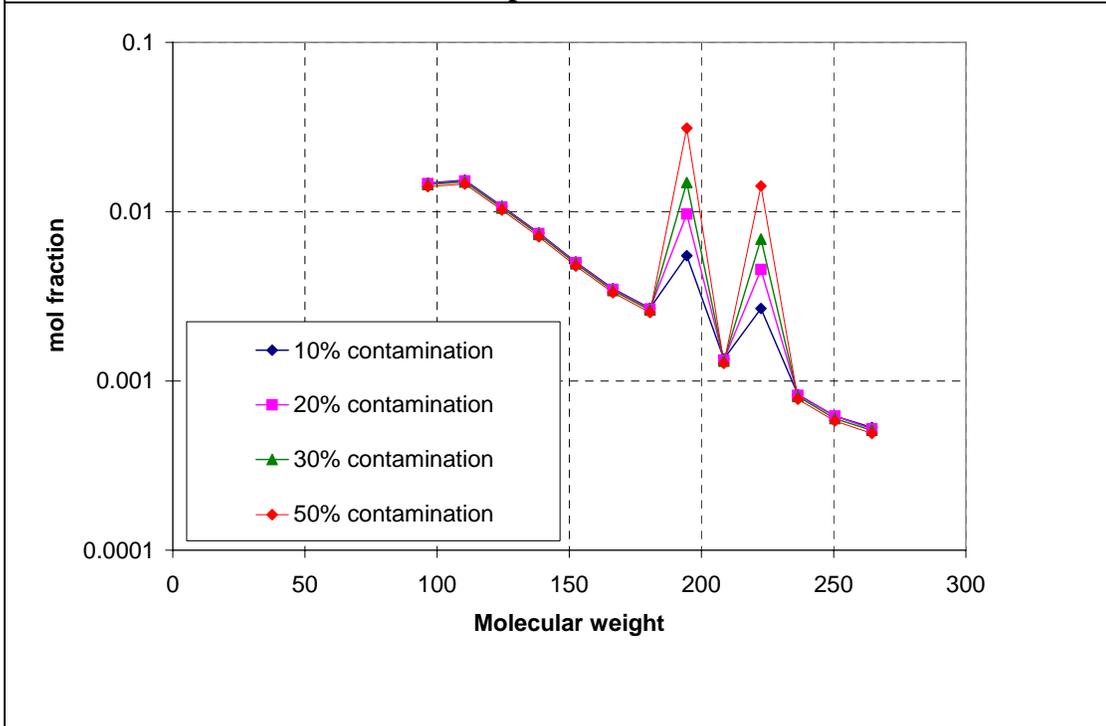


Figure 23. Molar distribution for wellstream sample at 20% contamination, and fit with exponential distribution. SPE3 fluid, 2-component OBM.

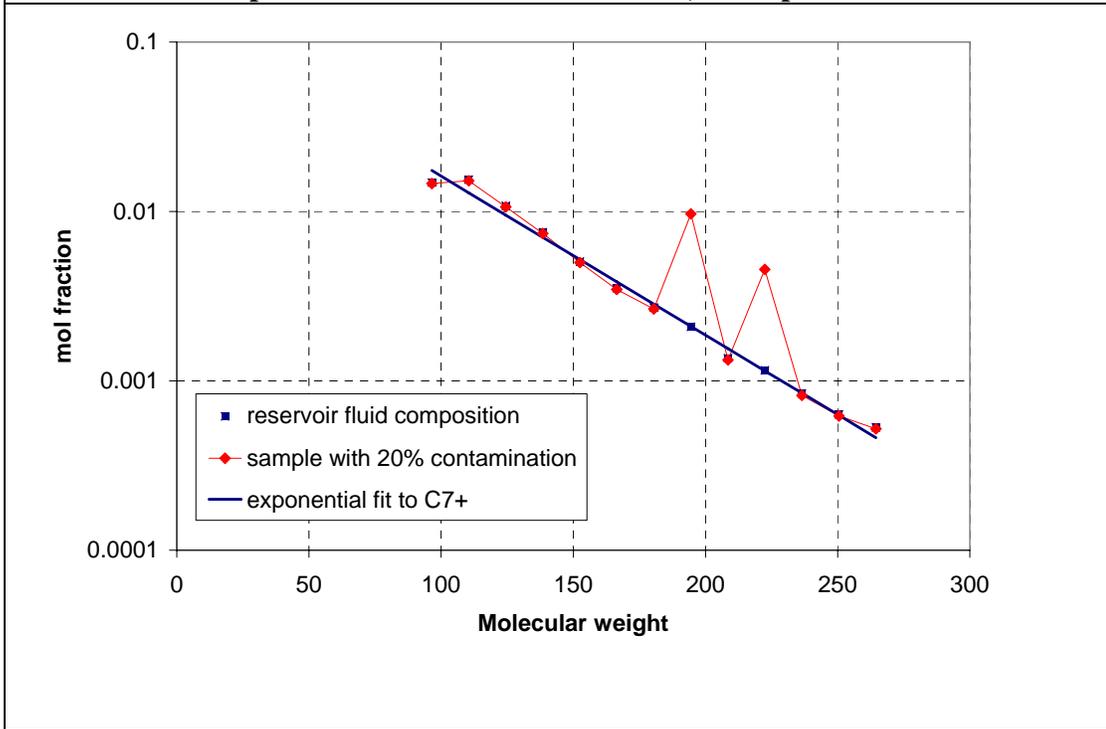


Figure 24. Molar distribution for contaminated wellstream samples. SPE3 fluid, diesel OBM.

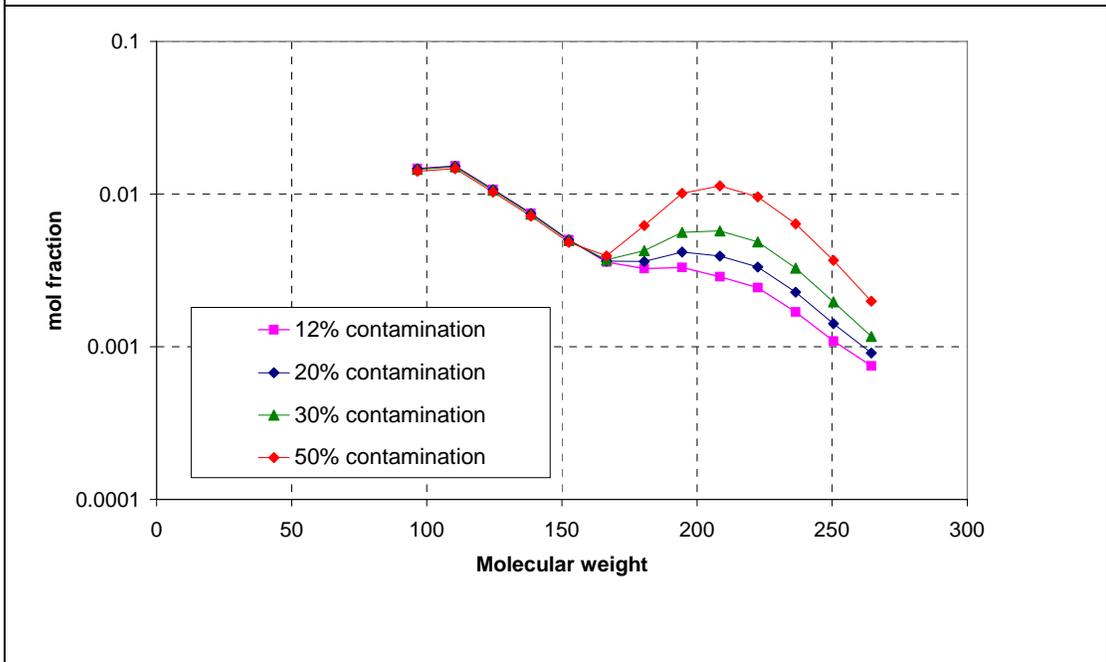


Figure 25. Molar distribution for wellstream sample at 20% contamination, and fit with exponential distribution and 'skimming' method. SPE3 fluid, diesel OBM.

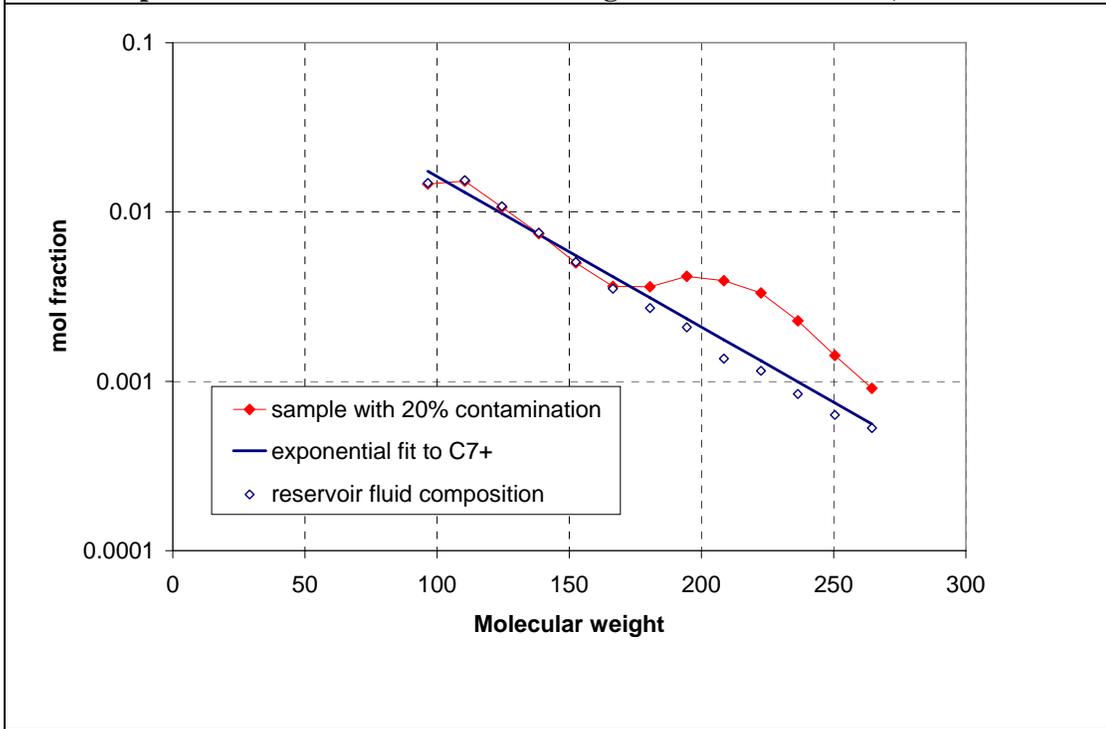


Figure 26. Molar distribution for wellstream sample at 20% contamination, and fit with exponential distribution and 'subtraction' method. SPE3 fluid, diesel OBM.

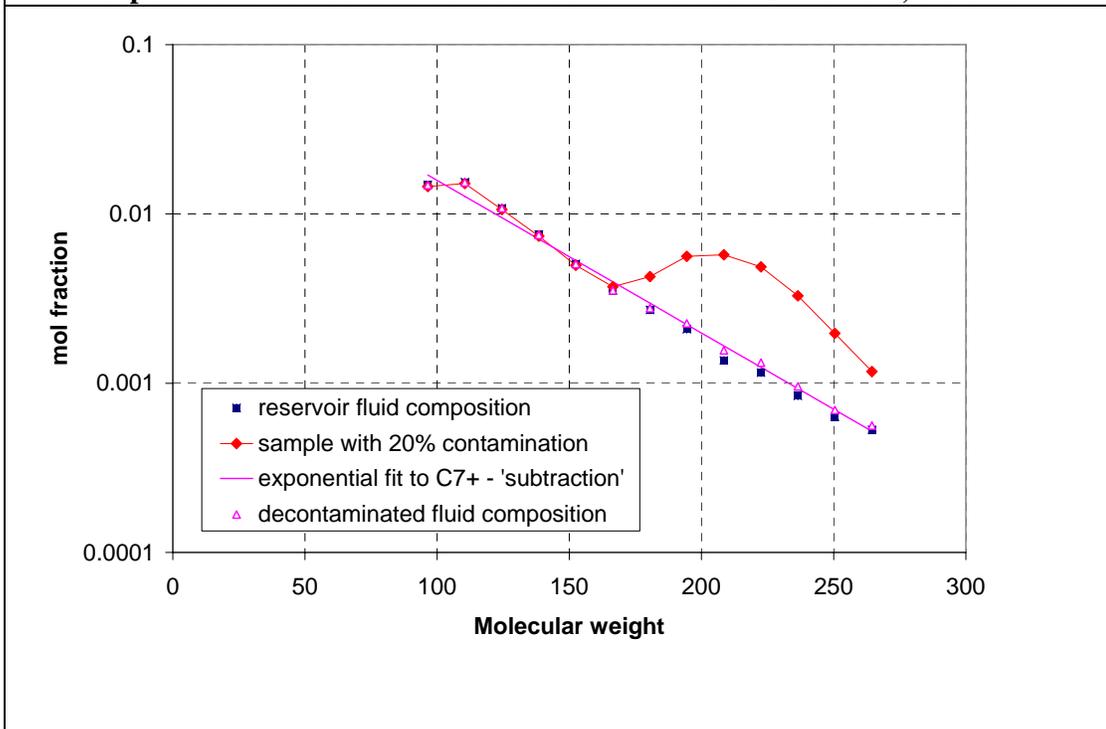


Figure 27. Molar distribution for contaminated wellstream samples. NS-1L fluid, 2-component OBM.

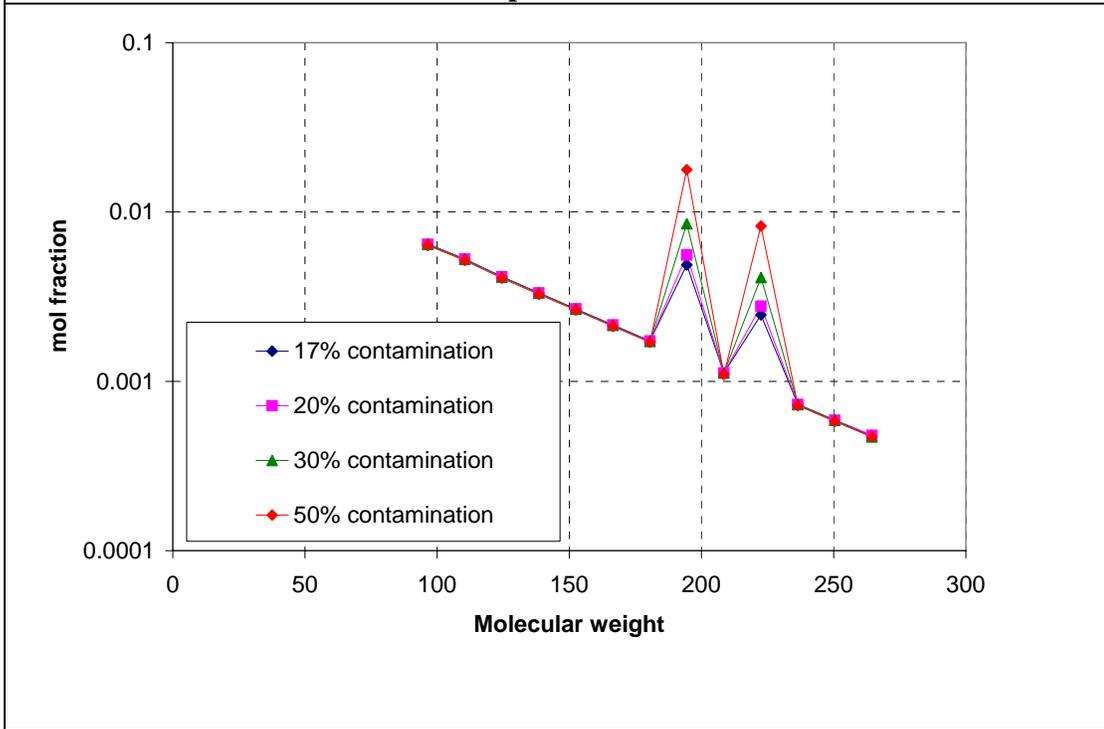


Figure 28. Molar distribution for sample at 20% contamination, and fit with exponential distribution. NS-1L fluid, 2-component OBM.

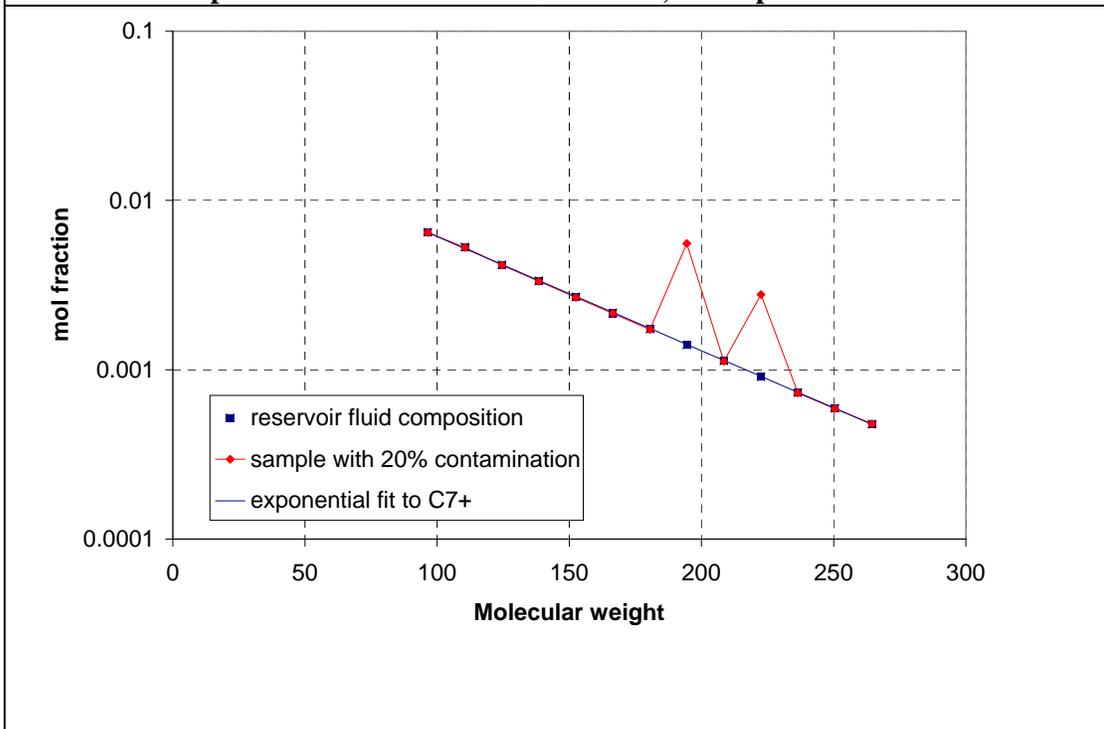


Figure 29. Molar distribution for contaminated wellstream samples. NS-1L fluid, diesel OBM.

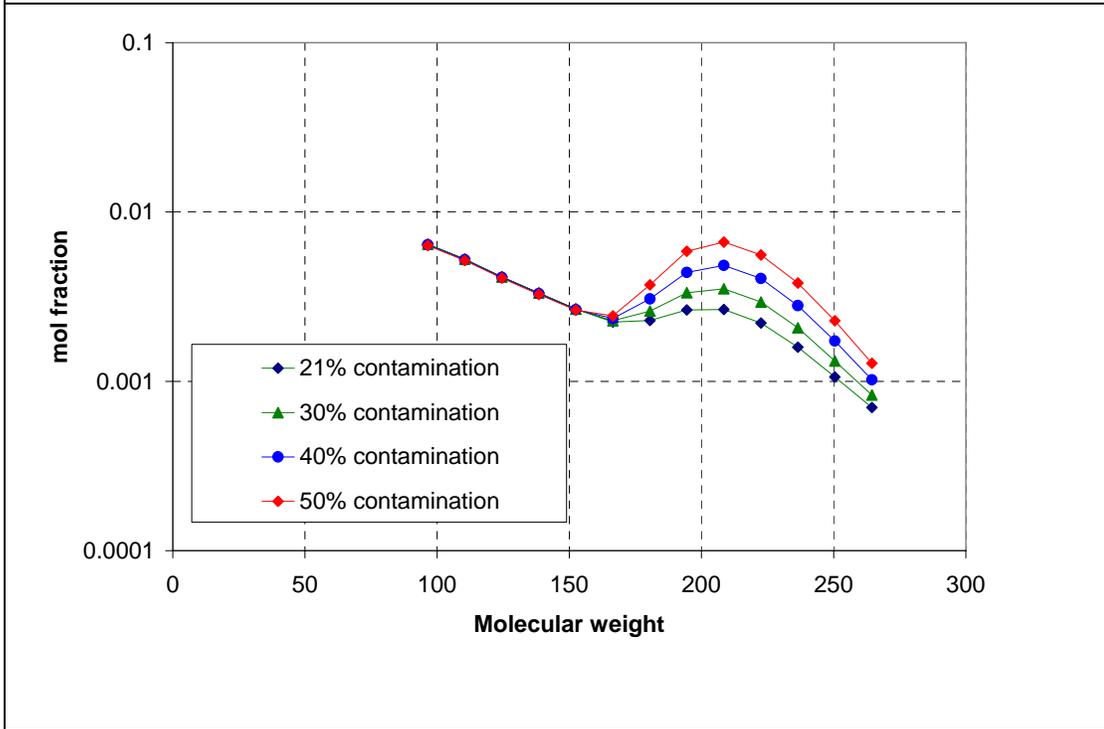


Figure 30. Molar distribution for wellstream sample at 20% contamination, and fit with exponential distribution. NS-1L fluid, diesel OBM.

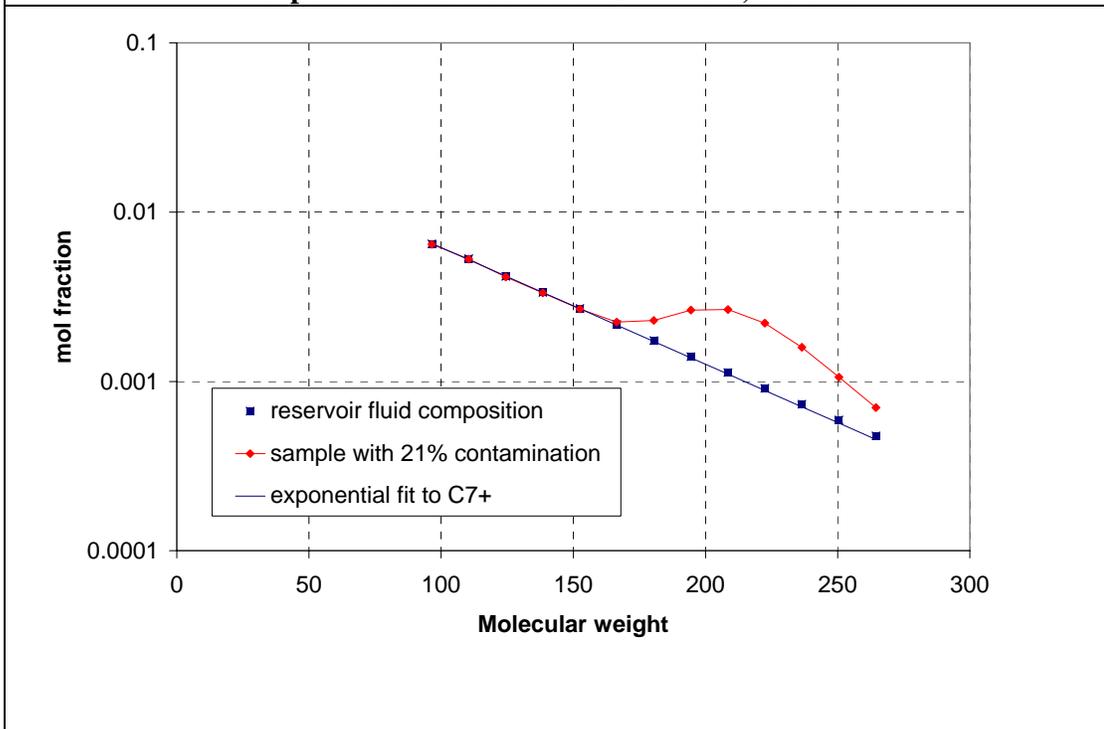


Figure 31. C7+ mol fraction in gas phase during CVD – SPE3 fluid contaminated with 2-component OBM.

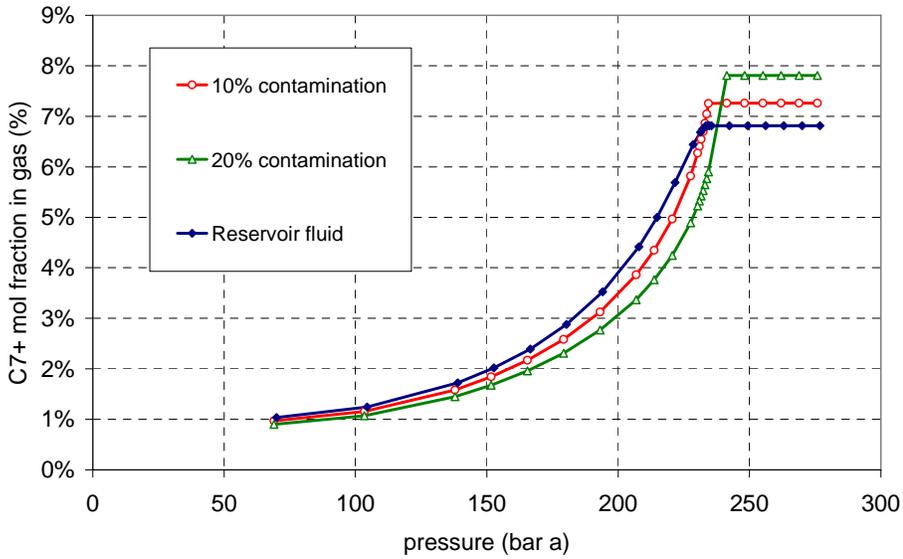
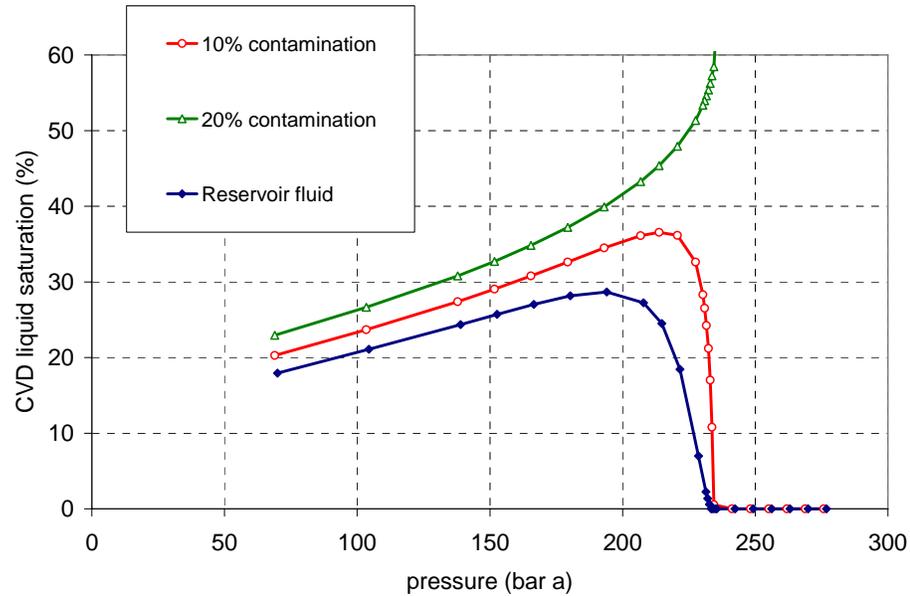


Figure 32. Liquid saturation during CVD – SPE3 fluid contaminated with 2-component OBM.



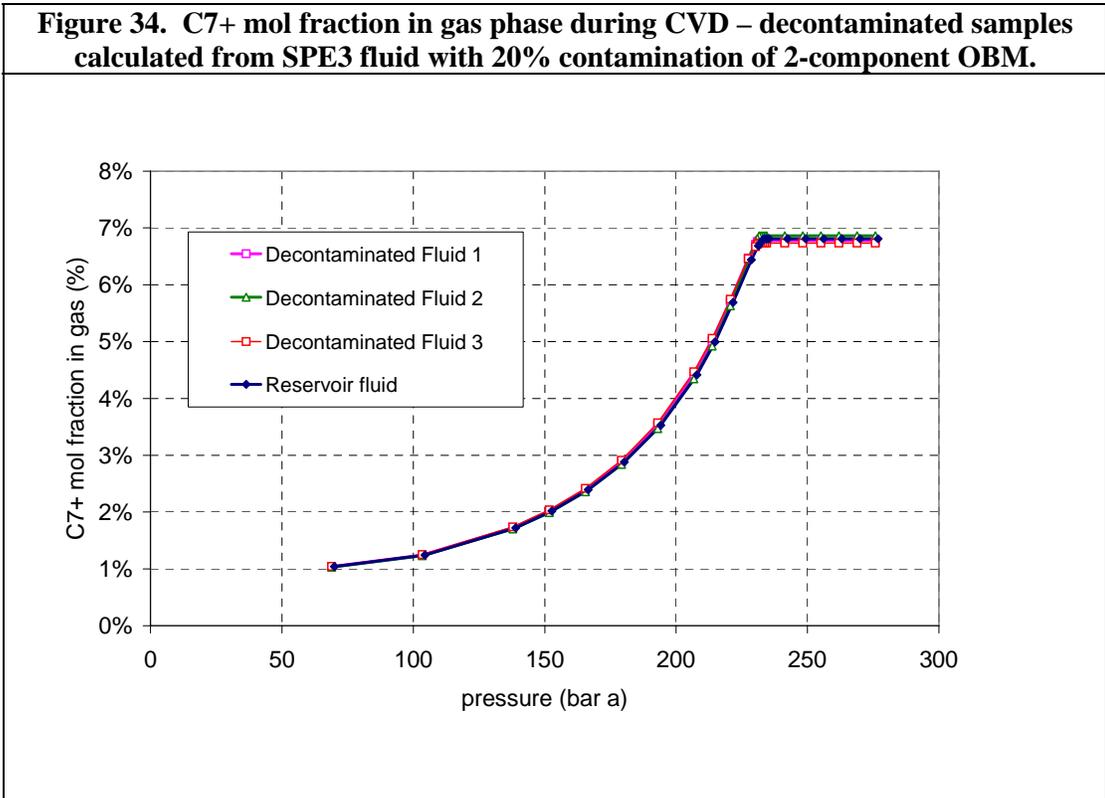
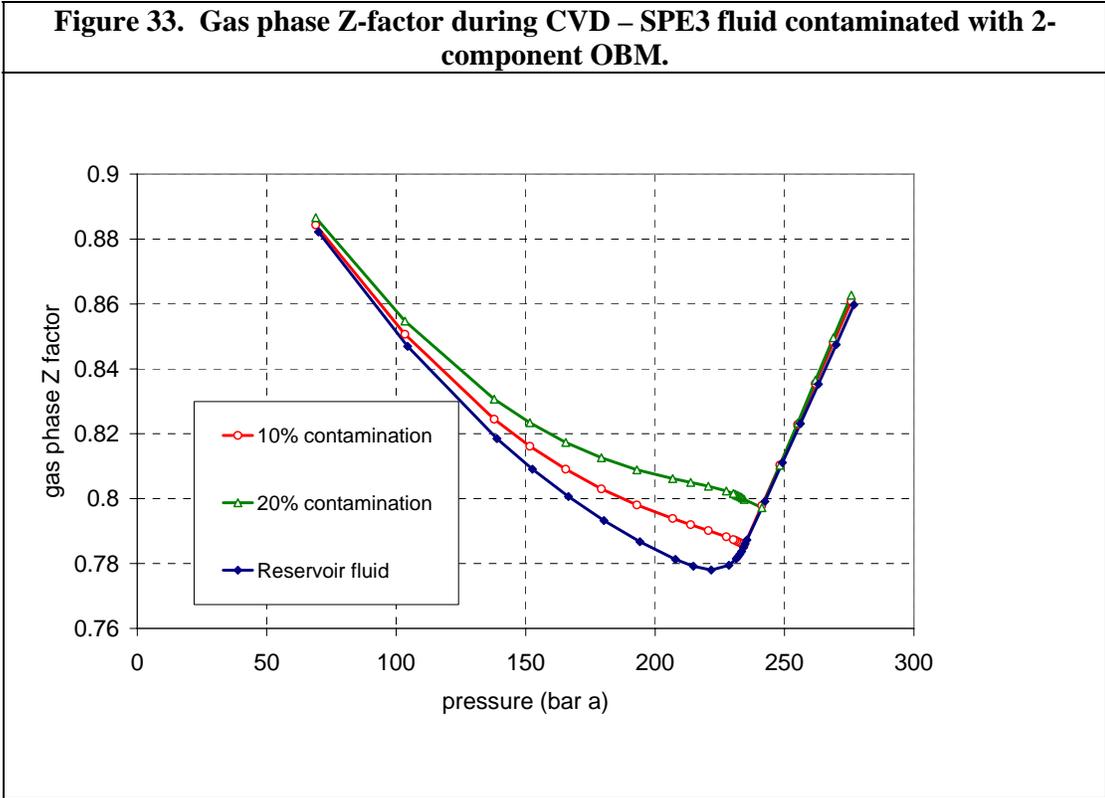


Figure 35. Liquid saturation during CVD – decontaminated samples calculated from SPE3 fluid with 20% contamination of 2-component OBM.

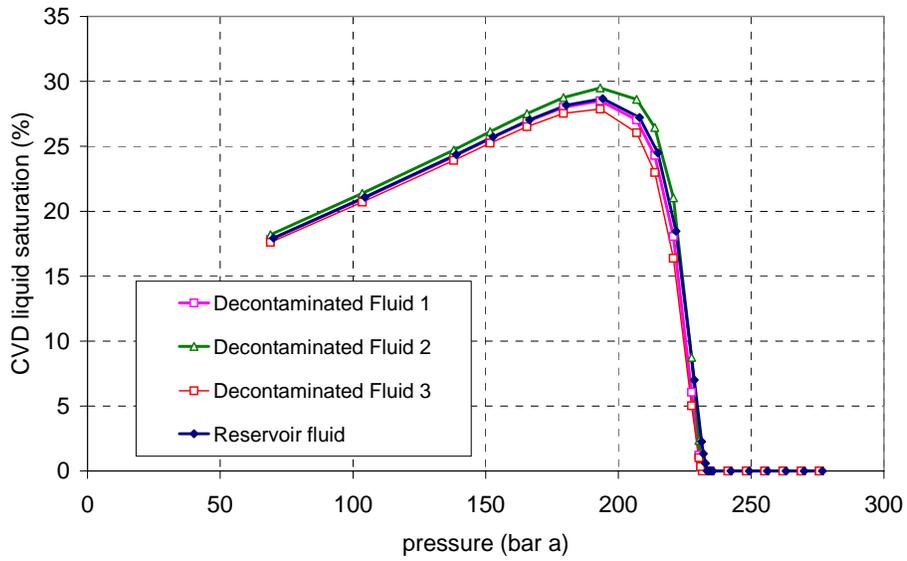


Figure 36. Gas phase Z-factor during CVD – decontaminated samples calculated from SPE3 fluid with 20% contamination of 2-component OBM.

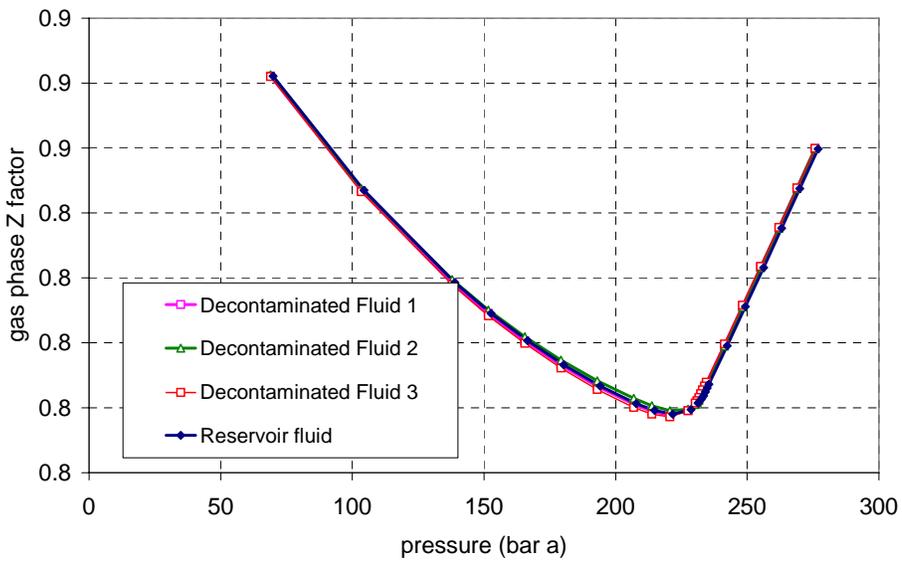


Figure 37. C7+ mol fraction in gas phase during CVD – SPE3 fluid contaminated with diesel OBM.

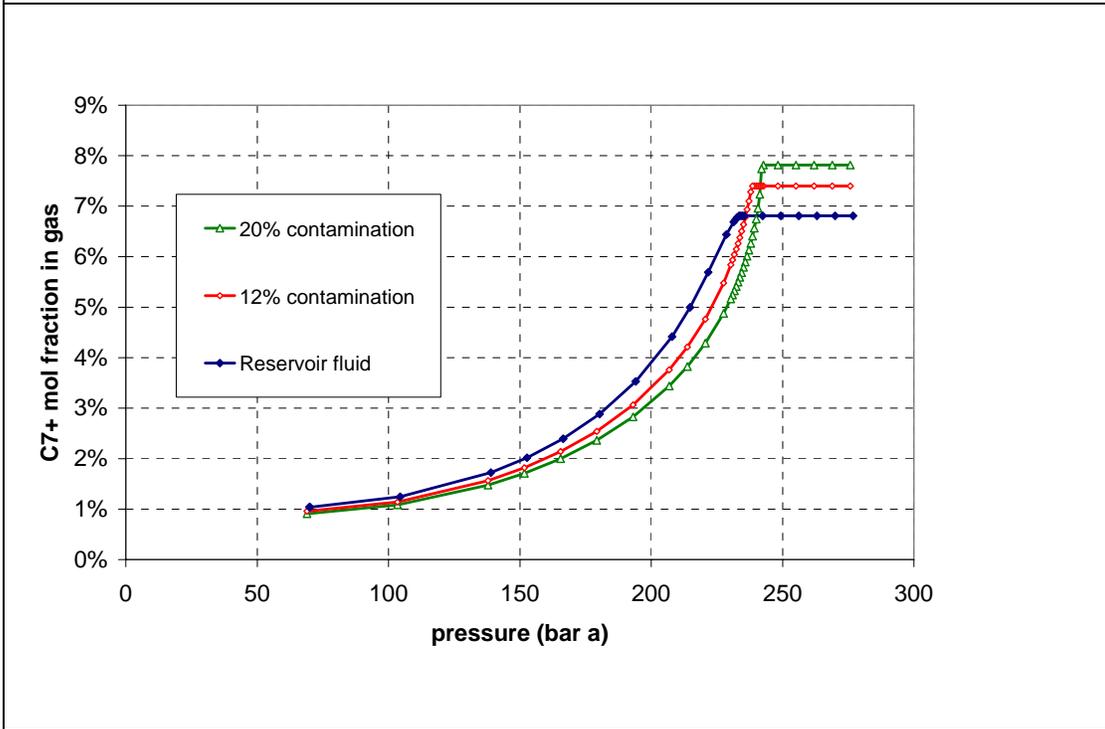


Figure 38. Liquid saturation during CVD – SPE3 fluid contaminated with diesel OBM.

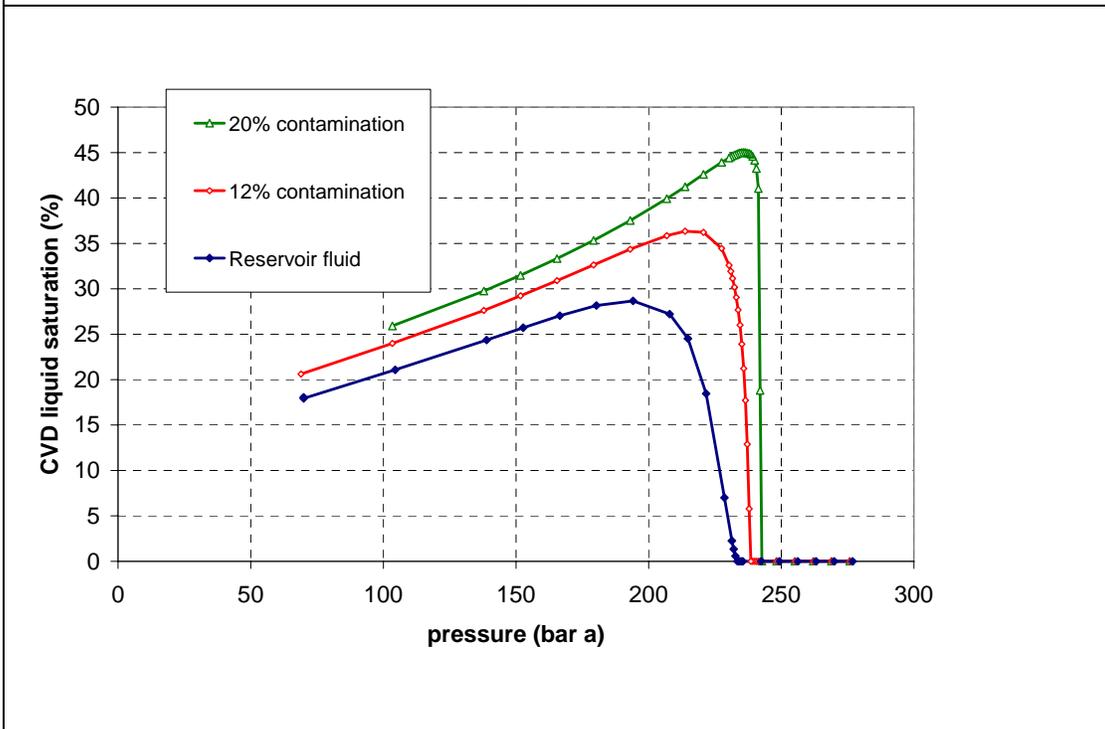


Figure 39. Gas phase Z-factor during CVD – SPE3 fluid contaminated with diesel OBM.

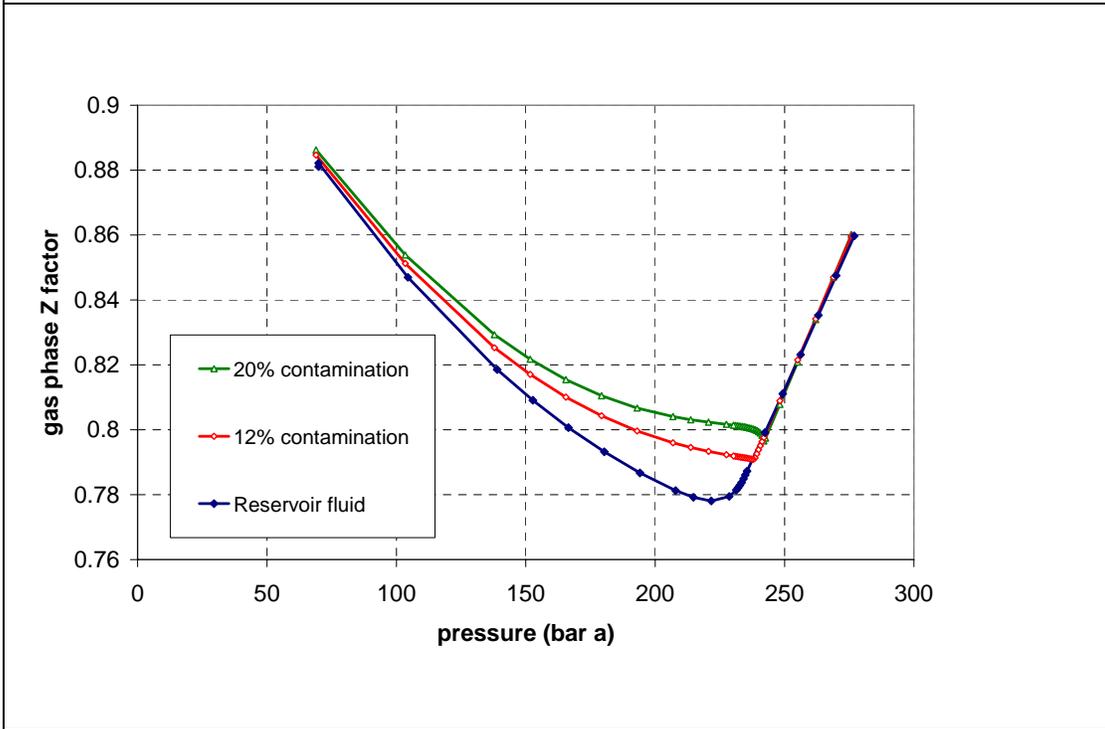


Figure 40. C7+ mol fraction in gas phase during CVD – decontaminated samples calculated from SPE3 fluid with 20% contamination of diesel OBM.

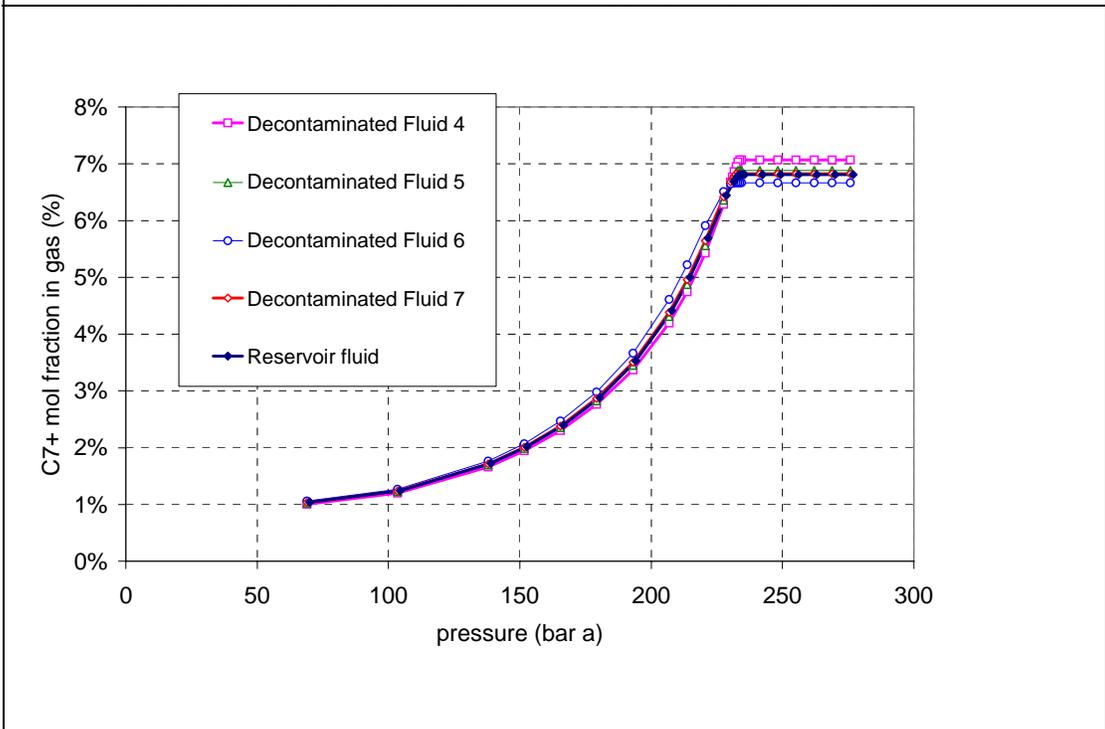


Figure 41. Liquid saturation during CVD – decontaminated samples calculated from SPE3 fluid with 20% contamination of diesel OBM.

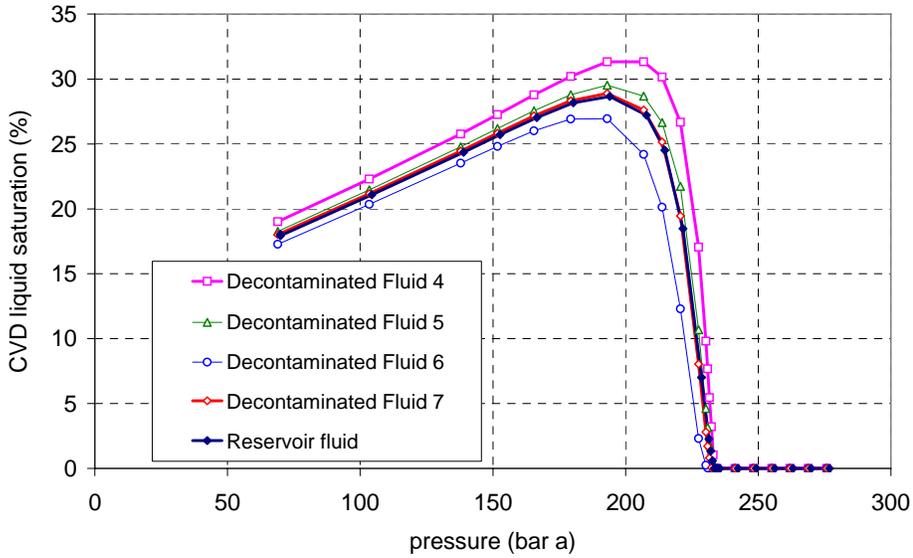
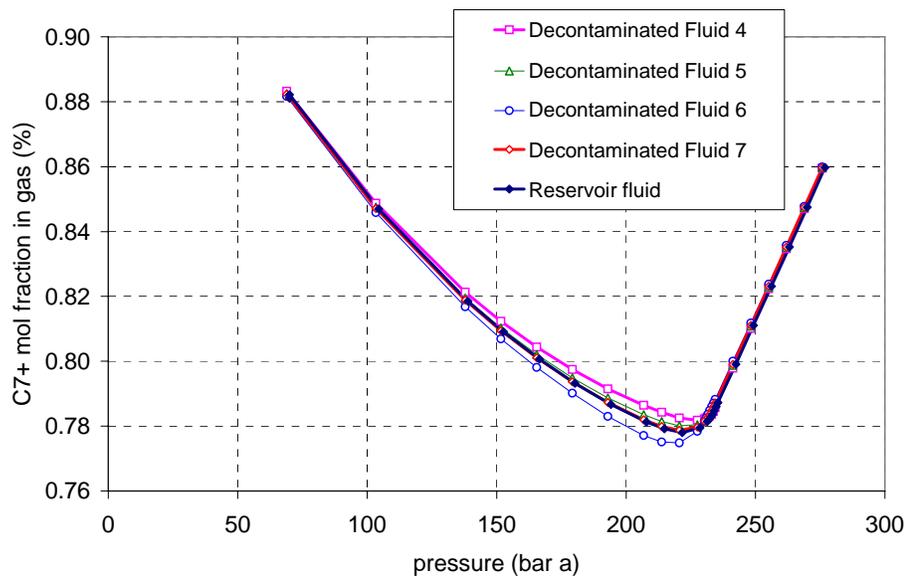


Figure 42. Gas phase Z-factor during CVD – decontaminated samples calculated from SPE3 fluid with 20% contamination of diesel OBM.



File references for Figures

Figs 1-7 PVT figures for report.xls

Fig 8 OBM radial grid.ppt

Fig 9 A1 & A1F2 maps.xls

Fig 10 Initial OBM distribution.xls

Figs 11 & 12 Figs 11,12,15.xls

Figs 13 & 14. A1I2plots vs time.xls

Fig 15 Figs 11,12,15.xls

Figs 16-18. A1 & A1F2 maps.xls

Fig 19-21. C7+ comp in wellstream.xls

Figs 22-30. Fit with simple model, SPE3, diesel.xls and similar

Fig 31-36 PVT Figures SPE 3 decontamination.xls

Fig 37-42 PVT Figures SPE 3 decontamination diesel.xls