SIMULTANEOUS DETERMINATION OF RELATIVE PERMEABILITY AND CAPILLARY PRESSURE USING DATA FROM SEVERAL EXPERIMENTS

A. Sylte[(1)], E. Ebeltoft[(2)] and E.B. Petersen[(3)]
[(1)]Norsk Hydro ASA, [(2)]Petec Software & Services AS and [(3)]Statoil ASA

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Abu Dhabi, UAE, 5-9 October, 2004

ABSTRACT

Simultaneous determination of relative permeability and capillary pressure curves by including more than one set of experimental data in the interpretation process is presented. A numerical simulator is introduced for history matching purposes to avoid the analytical assumptions traditionally used by the industry. Both synthetic as well as real experimental cases are utilised and analysed. The main contribution from this paper is that data from several types of experiments – such as centrifuge, unsteady state and steady state – may be utilized simultaneously in the history matching approach. Compared to traditional approaches, this have several potentially advantageous effects, including simplified and consistent handling of different type of experimental data, and accuracy improvement as different experiments carry information in different regions of the flow properties.

INTRODUCTION

Determination of relative permeability involves a multi-phase experiment on a core sample. During the experiment, data are gathered and subsequently analyzed to determine the relative permeability curves. Typical experiments include steady and unsteady state as well as centrifugation. Common for the data analyses techniques is that a series of assumptions (such as negligible capillary pressure) have been made in order to simplify the data analysis. This may lead to erroneous relative permeability curves, and potentially also make the relative permeability seem rate and/or process dependent [1, 2].

Frequently, numerical simulators have been introduced to avoid such assumptions [3-9]. In this approach, a simulator has been used to history match the experimental data in an implicit methodology in order to determine the relative permeability and capillary pressure curves. This methodology has been developed, tested and reported in a series of papers [5-8]. Using this method, the relative permeability and capillary pressure curves can be determined simultaneously from one single experiment. However, the accuracy of the flow properties might not be sufficient in the entire saturation range. Figure 1 shows schematically for which saturation ranges the different experiments typically contain significant relative permeability information. Outside these ranges, the obtained curves should be regarded as inaccurate. By combining data from at least two experiments (e.g., unsteady or steady state and single speed centrifuge), accurate relative permeability curves could be obtained in most of the saturation interval. By using additional data from an experiment mainly influenced by capillary forces (e.g., multi speed centrifuge), simultaneous information about both the relative permeability and the capillary pressure will be gained [9].

In order to determine one single set of flow functions based on data from several different experiments, the commercial core flow simulator Sendra [10] has been extended with a new feature. This new feature is further referred to as the multi-scenario feature. The multi-scenario feature allows us to utilize data from different experiments simultaneously in the history matching process leading to one set of flow properties.

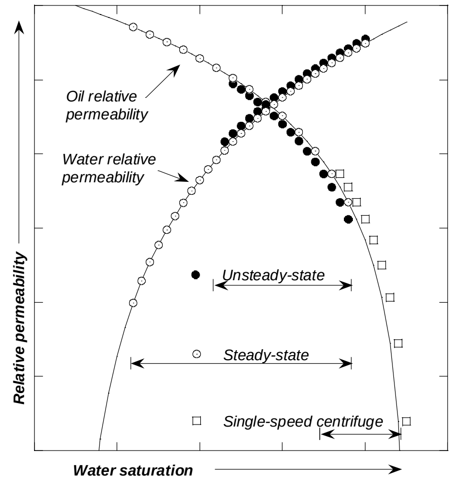

Figure 1: Relative permeability information from various experimental scenarios.

Throughout this paper it is assumed that there exists one single set of flow properties, independent of the flow process under consideration and where the different scaling criteria are within standard limits [11-13]. It will be demonstrated that it is possible to obtain one set of flow properties that simultaneously reconcile more than one set of experimental data on neighbouring core samples. In addition, we show that the accuracy is improved using the multi-scenario feature compared to the individual interpretation.

SYNTHETIC STUDY: RESULTS AND DISCUSSION

To test and evaluate the multi-scenario feature, a synthetic simulation study has been designed. An initial synthetic study is preferable, as we then know the true flow properties, and the robustness and importance of the suggested approach more readily can be evaluated. The simulator is used to generate true data points (i.e., oil production and/or pressure drop). To mimic measured data points, noise (with zero mean and a given standard deviation) is added to these true or simulated values, creating ”experimental” data points. We then attempt estimating the flow properties by changing parameters representing the functions (properties) in such a way that the discrepancy between the simulated data points and the ”experimental” data is minimized [5-8].

Two cases are considered; (1) the different experimental scenarios have *equal* flow properties in order to test the methodology and assess the accuracy, and (2) the different experimental scenarios have *unequal* flow properties in order to further test the methodology and assess the influence of the amount of experimental data and their accuracy.

Equal flow properties.
Three different experimental scenarios are used to demonstrate the multi-scenario feature and that the accuracy will be improved using this feature compared to the individual evaluation of the scenarios. To assess the accuracy with which the flow properties can be estimated, a linearized covariance analysis [14] is utilised together with B-spline representation [15] of the flow properties.

The three experimental scenarios utilised are (1) a steady state flow experiment, (2) a single speed centrifuge experiment and (3) a multi speed centrifuge experiment. These scenarios have been selected to gain data sensitive to the relative permeability in most of the saturation range according to Figure 1, together with capillary pressure information. All are so-called imbibition cases where oil is displaced by water from initial low water saturation; see Table 1 for core and fluid properties. The generated data from the steady state flow experiment, the single rate centrifuge experiment and the multi speed centrifuge experiment are interpreted using the multi-scenario feature.

Table 1: Core and fluid properties for synthetic case.

	Steady-state	**Single-speed (SS) centrifuge**	**Multi-speed (MS) centrifuge**
L [cm]	25.0	5.0	5.0
D [cm]	3.75	3.75	3.75
$k_o(S_{wi})$ *[mD]*	250.0	250.0	250.0
S_{wi} *[frac.]*	0.15	0.15	0.15
S_{or} *[frac.]*$^{*)}$	0.20	0.20	0.20
Φ *[frac.]*	0.212	0.212	0.212
μ_w *[cp]*	0.36	0.36	0.36
μ_o *[cp]*	1.2	1.2	1.2
ρ_w *[g/cm^3]*	1.021	1.021	1.021
ρ_o *[g/cm^3]*	0.780	0.780	0.780
Rotation axis [cm]$^{**)}$	-	13.715	13.715
Flow rates [ml/min]/ Centrifugal speeds [rpm]	Oil: 1.99; 1.88; 1.56; 1.0; 0.44; 0.12; 0.016; 0.0 Water: 0.01; 0.12; 0.44; 1.0; 1.56; 1.88; 1.984; 12.0	4000	700; 1000; 1400; 2000; 3000; 4000

$^{*)}$ From simulations when $k_{ro}=10^{-6}$
$^{**)}$ From the centre of the centrifuge to the centre of the core sample.

Figures 2-4 show the history matching results for the multi-scenario feature. It is observed that all three experiments are very well reconciled by simulation. The obtained flow properties were consistent with the true curves initially selected.

Figures 5-8 show the determined flow properties using the multi-scenario feature together with confidence intervals calculated from the linearized covariance analysis for both the multi-scenario feature and individual analysis. Both the relative permeability and the capillary pressure curves are accurately determined in the entire saturation range using the multi-scenario feature. Compared to the confidence interval for the individual analysis, the accuracy is improved for the relative permeability, but behaves almost equal for the capillary pressure. The data from the steady state experiment will contribute with information for the relative permeabilities in most of the saturation range, except for high water saturation. For high water saturation, the data obtained from the single speed centrifuge will contain information for the oil relative permeability. For low water saturation, the data obtained from the multi speed centrifuge will contain information for the water relative permeability [7]. Finally, the data from the multi speed centrifuge experiment will contain information for the capillary pressure. As the capillary pressure is very sensitive to the multi-speed centrifuge data in general, the improvement by utilizing the multi-scenario feature is limited. However, some improvements are observed for low water saturation as the steady state experiment is somewhat influenced by the capillary pressure in this region.

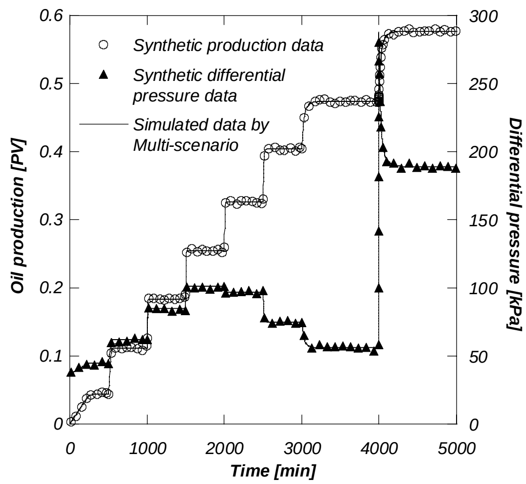

Figure 2: Reconciliation of the steady state data.

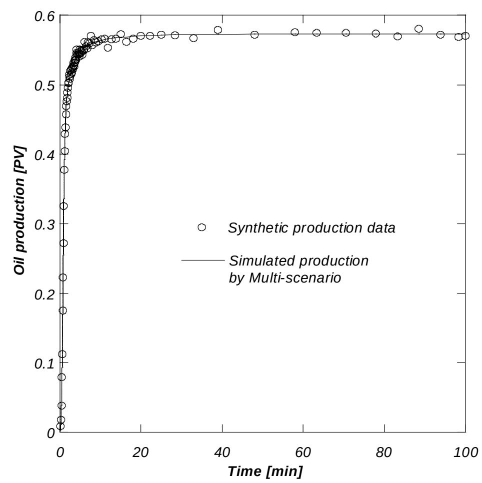

Figure 3: Reconciliation of the single speed centrifuge data.

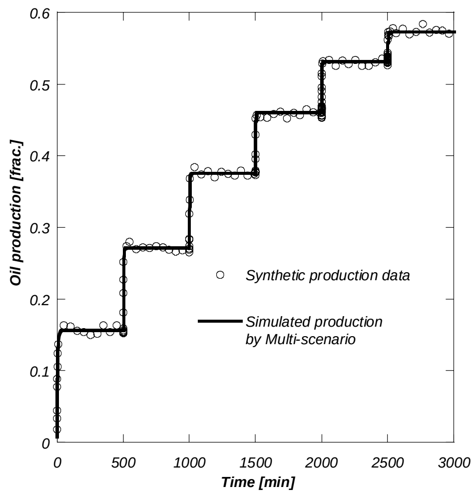

Figure 4: Reconciliation of the multi speed centrifuge data.

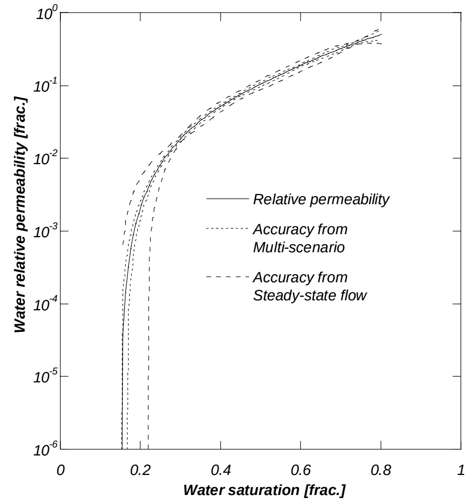

Figure 5: Water relative permeability from steady state data and multi-scenario estimation.

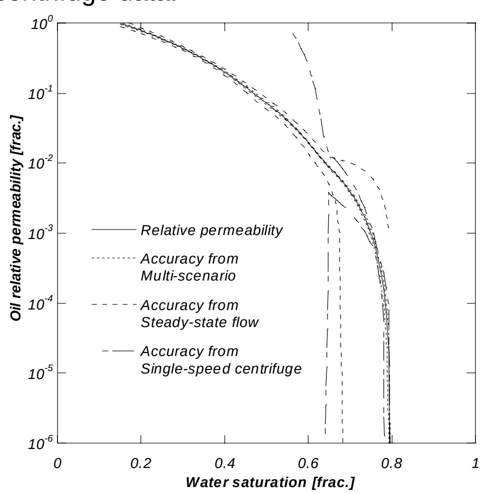

Figure 6: Oil relative permeability from steady state data, single speed centrifuge data.

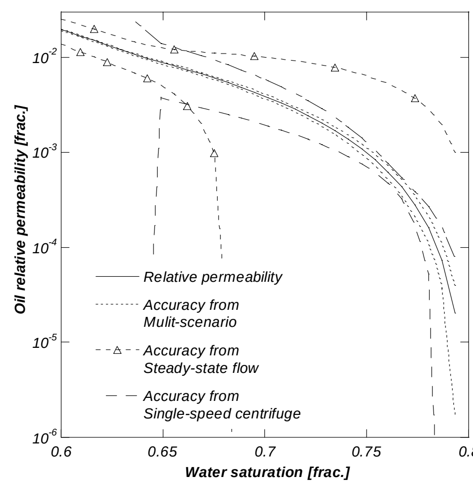

Figure 7: Oil relative permeability at high water saturations, magnification of Figure 6.

Unequal flow properties.

Throughout this paper it is assumed that the flow properties are equal independent of the flow process and where the different scaling criteria are within standard limits [11-13]. However, we have studied the effect of using the multi-scenario feature on two core samples (Core 1 and Core 2) that experience true different relative permeabilities. Water displacing oil steady state flow experiments are utilised for both core samples to demonstrate the multi-scenario feature, and to assess the influence of the amount of experimental data and their accuracy. The core and fluid properties for each steady state experiment are equal to the steady state experiment given in Table 1.

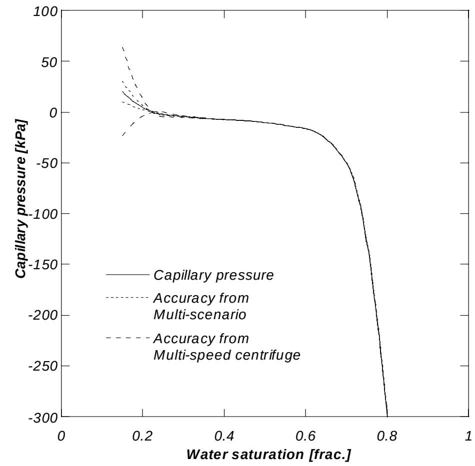

Figure 8: Capillary pressure from multi speed centrifuge data and multi scenario estimation.

<u>Equal amount of experimental data and equal experimental error</u>

Figure 9 shows the two true oil and water relative permeability curves and the estimated curves. Using the multi-scenario feature, an intermediate set of relative permeability curves are estimated. These intermediate relative permeabilities are the flow properties that best match both sets of the generated data.

<u>Different amount of experimental data and different experimental error.</u>

Two different cases are considered; (1) the amount of generated experimental data for Core 2 is around three times the amount of generated experimental data for Core 1, and (2) the experimental errors imposed on the generated experimental data for Core 1 is three times higher than the values imposed on the generated experimental data for Core 2.

Lower experimental error and more generated experimental data favour one of the experiments, in this case the experiment for Core 2. Both the amount of data and the standard deviation (experimental error) act as weighting of one of the experimental data set [8]. Figure 9 shows this effect. The curve represented by circles approach the relative permeability curve that is connected to the experiment with most generated data (Core 2). The curve represented by triangles approach the relative permeability curve that is connected with the less experimental errors (Core 2).

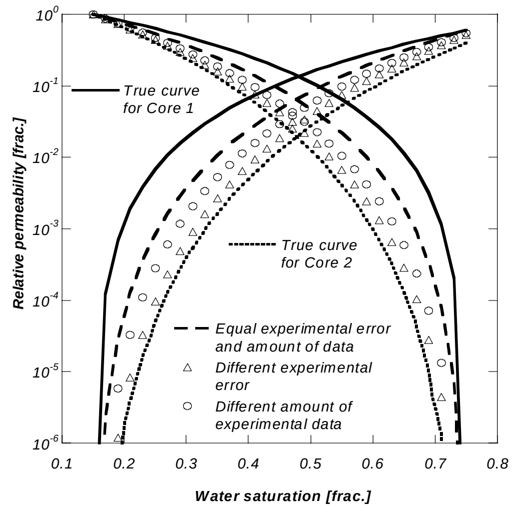

Figure 9: True and estimated relative permeability curves.

Experimental Study: Results and Discussion

The multi-scenario feature is further tested on real experimental cases using core samples from two different formations in the North Sea. All experiments are water displacing oil processes. Two different cases are considered; (1) using one steady state flow experiment, one multi speed centrifuge experiment and one single speed centrifuge experiment from one formation, and (2) using one unsteady state flow experiment and one multi speed centrifuge experiment from another formation.

All cores are properly selected prior to experimentation; CT-scans where utilized to ensure homogeneity and all samples within the same formation have been exposed to the same preparation procedure.

Experimental Study: Case 1

All core samples are restored-state and the steady state experiment has been performed at reservoir conditions while the centrifuge experiments have been performed at reservoir temperature and ambient pressure. The core samples used in the steady state flow experiment are a composite core of neighbouring plug samples. Another neighbouring core sample has been used for both the multi speed and single speed centrifuge experiments. The basic core and fluid properties are given in Table 2. Chierici correlation [16] has been used to represent the relative permeability curves and an extended Brooks and Corey correlation [17] has been used to represent the capillary pressure curve. See Appendix for details about the flow property representation.

Figure 10 and 11 show the relative permeability and capillary pressure curves, which reconciles all three experiments simultaneously, respectively. Based on the synthetic study, the steady state and single speed centrifuge experiments contribute with information about the relative permeabilities and the multi speed centrifuge experiment contribute with information about the capillary pressure. Hence, using all these experimental data simultaneously in the interpretation process, accurate flow properties are obtained in the entire saturation range.

Table 2: Core and fluid properties for Case 1.

	Steady-state	**SS cent.**	**MS cent.**
L [cm]	27.58	4.95	4.95
D [cm]	3.77	3.79	3.79
$k_o(S_{wi})$ *[mD]*	41	26	20.6
S_{wi} *[frac.]*	0.32	0.334	0.334
S_{or} *[frac.]* *)	0.10	0.10	0.10
Φ *[frac.]*	0.221	0.23	0.23
μ_w *[cp]*	0.352	0.526	0.526
μ_o *[cp]*	1.178	3.709	3.709
ρ_w *[g/cm³]*	n.m. (horizontal flow)	1.024	1.024
ρ_o *[g/cm³]*	n.m. (horizontal flow)	0.837	0.837
Rotation axis [cm] **)	-	13.74	13.74
Flow rates [ml/min]/ Centrifugal speeds [rpm]	Oil: 1.984; 0.47; 0.234; 0.15; 0.066; 0.03, 0.008; 0.0 Water: 0.016; 0.03; 0.066, 0.15; 0.234; 0.47; 0.992; 1.667; 6.667	3200	300; 700; 1000; 1450; 2150; 3100; 4550; 6500;

*) From simulations when $k_{ro}=10^{-6}$

**) From the centre of the centrifuge to the centre of the core sample.

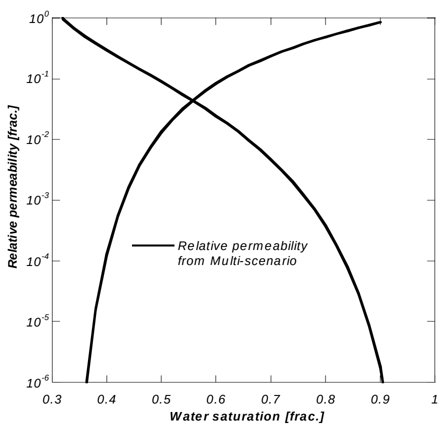

Figure 10: Estimated relative permeabilities using the multi-scenario feature.

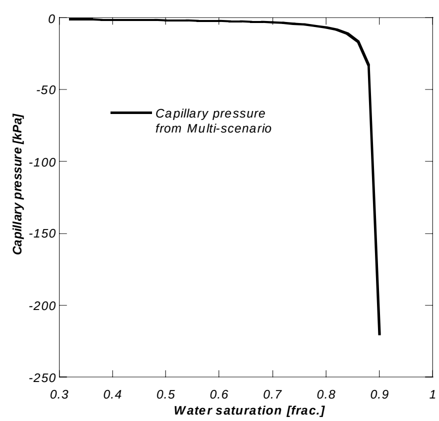

Figure 11: Estimated capillary pressure using the multi-scenario feature.

Figures 12-14 show the reconciled experimental data by simulating the experiments with the estimated flow properties in Figures 10 and 11. All experimental data are well reconciled by using the single set of relative permeability and capillary pressure curves determined from the multi-scenario feature.

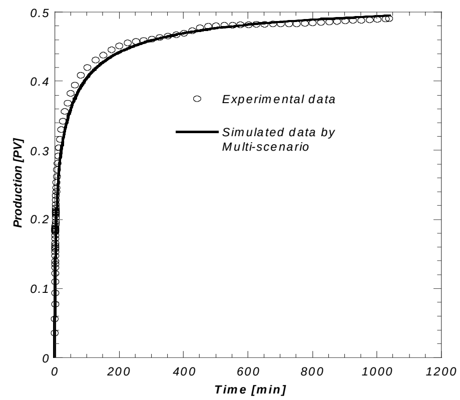

Figure 12: Reconciliation of the single-speed centrifuge experiment.

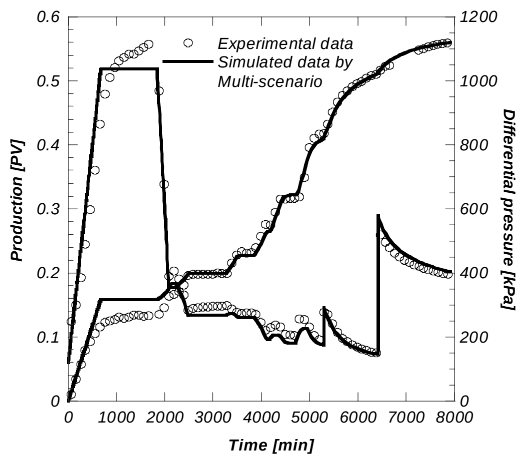

Figure 13: Reconciliation of the steady state experiment.

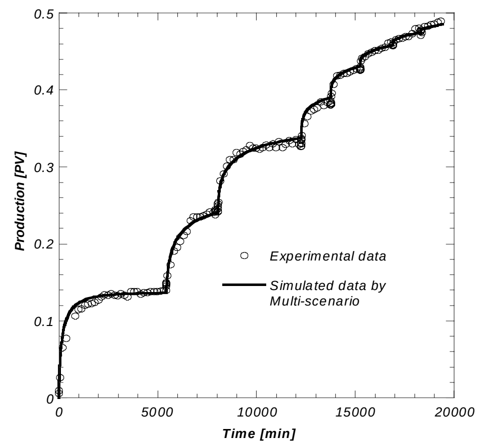

Figure 14: Reconciliation of the multi speed centrifuge experiment.

Experimental Study: Case 2

One vertical unsteady state flow experiment (injection from the bottom) and one multi-speed centrifuge experiment have been performed close to ambient conditions on one cleaned core sample. Note that the same core sample has been used for both the unsteady state and the centrifuge experiments. The basic core and fluid properties are given in Table 3. For this example, the Corey correlation [18] has been used for the relative permeability curve and an extended Brooks and Corey correlation [17] for the capillary pressure curve.

Table 3: Core and fluid properties for Case 2.

	Unsteady state	**Multi-speed centrifuge**
L [cm]	4.76	4.76
D [cm]	3.79	3.79
$k_o(S_{wi})$ *[mD]*	23.0	23.0
S_{wi} *[frac.]*	0.31	0.293 *)
S_{or} *[frac.]* **)	0.28	0.28
Φ *[frac.]*	0.171	0.171
μ_w *[cp]*	1.212	1.212
μ_o *[cp]*	1.274	1.274
ρ_w *[g/cm³]*	1.103	1.103
ρ_o *[g/cm³]*	0.762	0.762
Rotation axis [cm] ***)	-	14.22
Flow rates [ml/min]/ Centrifugal speeds [rpm]	Water : 0.09	500; 700; 1000; 1400; 2200; 3500; 5400

*) This value is before spontaneous imbibition, $S_w=0.543$ after spontaneous imbibition
**) From simulations when $k_{ro}=10^{-6}$
***) From the centre of the centrifuge to the centre of the core sample

Figures 15 and 16 show the estimated relative permeability and capillary pressure curves using the multi-scenario feature in the interpretation process, respectively. The experimental data from the multi speed centrifuge experiment does not contain information of the positive part of the capillary pressure curve. However, to reconcile the experimental data for the flow experiment the capillary pressure curve reveal positive values for low saturations. Nevertheless, this part of the capillary pressure curve, i.e. below S_w=0.543, cannot be regarded as accurate.

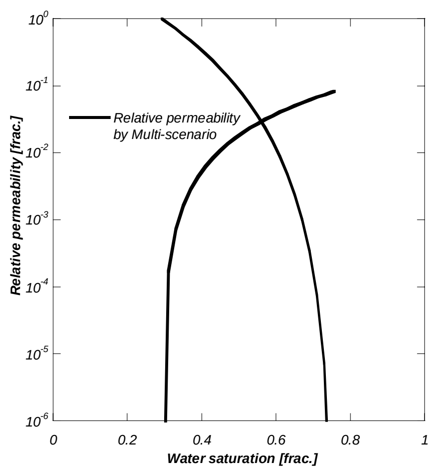

Figure 15: Estimated relative permeabilities using the multi-scenario feature, Corey representation.

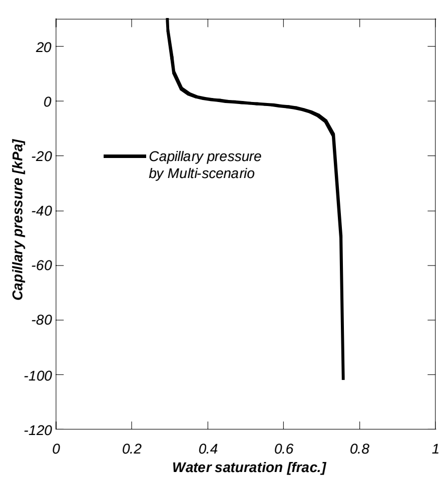

Figure 16: Estimated capillary pressure using the multi-scenario feature, Extended Corey and Brooks representation.

Figures 17 and 18 show the reconciled experimental data by simulating the unsteady state and multi speed centrifuge experiments with the estimated flow properties in Figures 15 and 16. All experimental data are well reconciled by using the single set of relative permeability and capillary pressure curves determined from the multi-scenario feature.

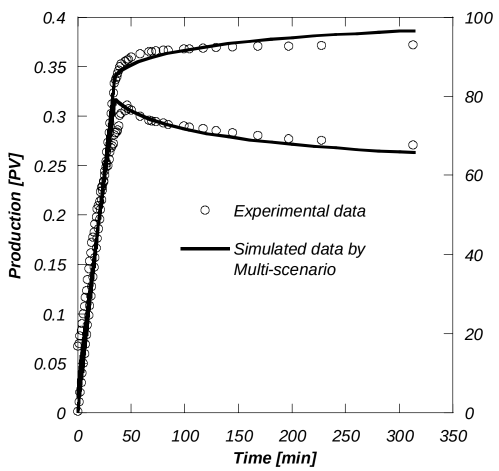

Figure 17: Reconciliation of the unsteady state experiment by the multi-scenario feature.

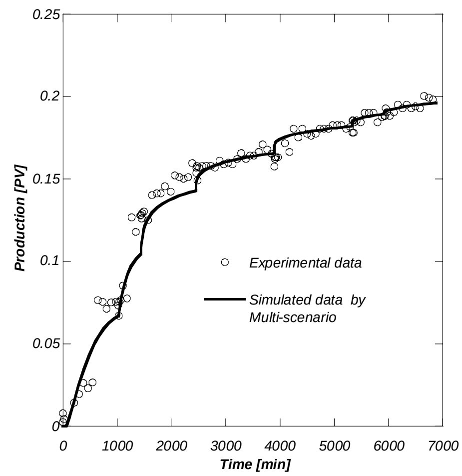

Figure 18: Reconciliation of the multi speed centrifuge experiment.

CONCLUSIONS

Following conclusions can be drawn from this work:

1. It is possible to determine one set of relative permeability and capillary pressure curves which reconcile several experiments simultaneously using the multi-scenario feature,
2. The accuracy of the determined flow properties using the multi-scenario feature is improved compared to the individual analyse as more information is available,
3. If the flow properties are actually different for different experimental scenarios, the obtained relative permeability will take an intermediate value if properly used with respect to the amount of data and their accuracy. If not properly used, the estimated relative permeability approaches the curve with most experimental data and/or with lowest experimental errors, i.e. lowest standard deviation.

ACKNOWLEDGEMENTS

The authors acknowledge Shell, Conoco-Norge, Norsk Hydro and Statoil for financial support of this work. Special thanks to Norsk Hydro and Statoil for the permission to publish the experimental results.

NOMENCLATURE

Φ	Porosity
D	Diameter
L	Length of core
k_{ro}	Relative permeability to oil
k_{rw}	Relative permeability to water
S_{wi}	Irreducible water saturation
S_{or}	Residual oil saturation
μ_o	Viscosity to oil
μ_w	Viscosity to water
ρ_o	Density to oil
ρ_w	Density to water

REFERENCES

1. Jack Haugen: "Unsteady state displacement combined with centrifuge technique for measurement of relative permeability", reviewed Proceedings of the Society of Core Analysts Third European Core Analysis Symposium, Paris, France, September 14-16, 1992.
2. Nordtvedt, J.E., Urkedal, H., Ebeltoft, E., Kolltveit, K., Petersen, E.B., Sylte, A., Valestrand, R., "The Significance of Violated Assumptions on Core Analysis Results", reviewed Proceedings of the 1999 International Symposium of the SCA, Golden, Colorado USA, August 1-4, 1999.
3. Poulsen, S., Skauge, T., Dyrhol, S.O., Stenby, E., Skauge, A.: "Including Capillary Pressure in Simulations on Steady State Relative Permeability Experiments", Reviewed Proceedings of the 2000 International Symposium of the SCA, Abu Dhabi, UAE, October 18-22, 2000.
4. Courtial, R., Ghalimi, S.: "Techniques for Relative Permeability Calculations: A Closer Look", Reviewed Proceedings of the 2000 International Symposium of the SCA, Abu Dhabi, UAE, October 18-22, 2000.
5. Watson, A.T., Richmond, P.C., Kerig, P.D., Tao, T.M.: "A Regression-Based Method for Estimating Relative Permeabilites from Displacement Experiments", *SPE Reservoir Engineering*, **3**, No. 3, 1988, 953
6. Kerig, P.D. and Watson, A.T.: "A New Algorithm for Estimating Relative Permeabilities from Displacement Experiments", SPERE (Feb. 1987), 103-12.
7. Nordvedt, J.E., Mejia, G., Yang, P., Watson, A.T.: "Estimation of Capillary Pressure and Relative Permeability Functions From Centrifuge Experiments", SPE Reservoir Engineering, Vol. 8, No. 4, Nov. 1993, pp. 292-298.
8. Kulkarni, R., Watson, A.T., Nordtvedt, J.E., Sylte, A.: "Two-Phase Flow in Porous Media: Property Identification and Model Validation", AIChE Journal, November 1998, Vol. 44, No. 11
9. Maas, J.G., Schulte, A.M.: "Computer Simulation of Special Core Analysis (SCAL) Flow Experiments Shared on the Internet", Reviewed Proceedings of the 1997 International Symposium of the SCA, Calgary, Canada, September 7-10, 1997.
10. Sendra, "User guide", Petec Software & Services, 2003.
11. Skauge, A., Thorsen, T., Sylte, A.:"Rate Selection for Waterflooding of Intermediate Wet Cores", Reviewed Proceedings of the 2001 International Symposium of the SCA, Edinburgh, September 17-19, 2001.

12. Lake, L.W.: *Enhanced Oil Recovery*, Prentice Hall, New Jersey, 1989, 70-73, 145-147.
13. Rapoport, L.A. and Leas; W.J.:"Properties of linear waterfloods".*Trans* AIME, 1953, 198, (139-148)
14. Kerig, P.D. and Watson, A.T.: "Relative Permeability Estimation From Displacement Experiments: An Error Analysis ", SPE Res. + Eng., 175-182, Febr. 1986.
15. Schumaker, L.L.: "Spline functions: Basic Theory," J. Wiley & Sons Inc., New York City, 1981
16. Chierici, G.L.: "Novel Relations for Drainage and Imbibition Relative Permeabilities", SPEJ, June 1984, pp. 275-276.
17. Skjaeveland, S.M, Siqveland, L.M., Kjosavik, A., Hammervold Thomas, W.L., Virnovsky, G.A.: "Capillary Pressure Correlation for Mixed-Wet Reservoirs", SPE Reservoir Eval. & Eng. 3 (1), February 2000.
18. Corey, A.T.: "The Interaction Between Gas and Oil Relative Permeability", Prod. Mon., 19, 38, 1954.
19. Brooks, R.H., Corey, A.T.: "Properties of Porous Media Affecting Fluid Flow", J. Irrigat. Drainage Div., Proc. ASCE (1666) 92, No. IR2, 61.
20. Brooks, R.H., Corey, A.T.: "Hydraulic Properties of Porous Media", Hydraulic Paper No. 3, Colorado State U., 1964.

APPENDIX: FLOW FUNCTION REPRESENTATION

A key aspect in estimating multi-phase flow properties from measured data is the representation of the unknown functions; relative permeability and capillary pressure. It is essential that the relative permeability and capillary pressure correlations have sufficient degree of freedom to represent the true (although unknown) properties, yet it is desirable that the degree of freedom be limited whenever there is insufficient information content in the experimental data. It is also desirable that the representations of relative permeability and capillary pressure properties utilize the same residual saturations, S_{wi} and S_{or}. The Corey correlation [18] is well known and will not be outlined here. B-spline correlation has also been widely used the last decade [2, 4, 5-8, 15] and has also been left out in this Appendix. The correlation proposed by Chierici [16] for relative permeability and the relatively new correlation for capillary pressure proposed by Skjaeveland [17] is outline below.

Relative permeability: To ensure a flexible function but still maintain a smooth characteristic it is possible to use the correlation proposed by Chierici [16] for the relative permeability curves:

$$k_{rw} = k_{rw}\left(S_{or}\right) e^{\left(-D_1 R_n^{-D_2}\right)} \tag{A1}$$

$$k_{ro} = k_{ro}\left(S_{wi}\right) e^{\left(-D_3 R_n^{D_4}\right)} \tag{A2}$$

$$R_n = \frac{S_w - S_{wi}}{1 - S_{or} - S_w} \tag{A3}$$

Each of the relative permeabilities is represented by two parameters: D_1 and D_2 for the water relative permeability and D_3 and D_4 for the oil relative permeability. In addition, the saturation term, R_n is used. Only $S_{wi}, S_{or}, k_{rw}(S_{or})$ and $k_{ro}(S_{wi})$ have physical meaning. (A1) and (A2) are thus parameter equations where D_1, D_2, D_3, D_4 and R_n are empirical and used to ensure a flexible but smooth shape of the relative permeability curves. Note that the *R term* in (A3) is a correlation parameter quite different from normalized saturation.

Capillary pressure: To ensure asymptotic behaviour toward S_{or} we have used the correlation proposed by Skjaeveland et. al [17]. They extended the Brooks and Corey correlation [19, 20] to exhibit both the positive part and the negative part of the capillary pressure curve:

$$P_c = \frac{c_w}{\left(\frac{S_w - S_{wi}}{1 - S_{wi}}\right)^{a_w}} + \frac{c_o}{\left(\frac{1 - S_w - S_{or}}{1 - S_{or}}\right)^{a_o}} \tag{A4}$$

This correlation is symmetrical with respect to the two fluids since neither of them dominates the wettability. a_w and c_w are the parameters for the positive part while a_o and c_o are the parameters for the negative part. a_w, a_o and c_w are all positive number while c_o is negative.