# WATERFLOODINGS ON INTERMEDIATE WET POROUS MEDIA : NEW CONSIDERATIONS ON TWO PHASE FLOW PROPERTIES DETERMINATION.

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**Abstract** : A reliable residual oil saturation (SOR) determination is essential for an accurate forecast of recovery by water drive in oil reservoirs. Two phase flow properties (SOR, relative permeabilities and capillary pressure) are usually determined from waterflooding experiments. However, the remaining oil saturation (ROS) obtained from experimental waterflooding often over estimates the SOR value in the case of intermediate wettability (or oil wet media), especially for permeable media.

The aim of this study is to outline the relationship between experimental ROS obtained by various methods. Waterflooding experiments under gammaray monitoring and centrifugation experiments have been carried out on homogeneous core samples. Cores wettabilities have been previously determined by adapted techniques.

The ROS value determined by centrifuge techniques can be considered as representative of SOR, and centrifuge capillary pressure should be taken into account for the numerical interpretation of waterflooding. Consequently, the relative permeabilities values have to be determined between the waterflood ROS and the centrifuge one. This new approach

using both coreflood and centrifuge measurements allows a better two phase flow properties determination.

## INTRODUCTION

Experimental waterflooding representativity has already been studied by various authors. Some of them showed how relative permeabilities ($k_r$) and capillary pressure ($P_C$) can be determined by numerical history matching of the experimental results for a water wet medium (Labastie *et al.*, 1980; Hamon *et al.*, 1986) or for an intermediate or oil wet medium (Labastie *et al.*, 1980; Hamon et al., 1988; Vidal, 1990).

The standard Elf Aquitaine procedure, deduced from these works, consists in performing two tests :

- one high rate waterflooding (the front velocity is equal to about ten or twenty times the field one) where capillary forces can be neglected compared to viscous forces. The remaining oil saturation at the end of this experiment is assumed to be the residual one, and the numerical interpretation gives mainly the relative permeabilities which are not rate dependant (Labastie *et al.*, 1980)
- one low rate waterflooding (the front velocity is close to the field one) where capillary forces are not negligible anymore. The numerical history matching gives the imbibition capillary pressure curve and allows to improve the relative permeabilities determination.

Before both of these tests, the core sample is cleaned by strong solvents circulation, saturated in oil and water (initial water saturation) and wettability is restored by an aging period in stock tank oil. The experiments are usually performed on "full size" core samples (diameter between 50 and 100 mm, length between 20 and 30 cm).

The numerical interpretations are performed by a black oil numerical model based on generalized Darcy's law. Boundary conditions and other laboratory needs have been introduced in this specialized model. A good accordance between the experimental and numerical results for both floods confirms the reliability of this method.

For displacement of oil by gas injection, the capillary pressure curve to take into account is the drainage one. This curve, representative of an oil wettability, can be easily determined directly (porous plate) or indirectly (mercury injection). Based on this point, Delclaud *et al.* (1987) established a method to determine the gas/oil relative permeabilities : one gas flooding under high pressure drop is carried out and numerically simulated using the $P_c$ curve previously determined by an adapted technique. The oil relative permeability extrapolation between the gasflooding ROS and the real SOR is obtained by porous plate transient productions numerical interpretation. It also has been found that the static ROS is valid in dynamic conditions, but it is reached very slowly due to the very low oil permeability.

The aim of this study is to validate a simplified method for waterfloodings comparable to the one used for gasfloodings. The main difficulty in the water/oil case is to determine experimentally the imbibition $P_c$ curve needed. Some recent improvements in centrifuge techniques allowed us to find a such procedure.

## EXPERIMENTAL PROGRAM

Waterflooding and centrifuge experiments have been carried out on three kinds of core samples. Waterfloodings were performed at various rates or pressure gradient, using the classical Elf Aquitaine procedure. The core samples wettability evolution have been previously studied (see Appendix A). The imbibition capillary pressure curves have been determined by centrifugation, using a Beckman Ultracentrifuge. The experimental conditions are described in Table 1. More details on some experimental procedures or wettability restoration are given in Appendix A and B.

**TABLE 1 : Experimental conditions**

| *Rock type* | *N°* | *Experiments* | *Injection rate ($cm^3/h$)* | *Wettability Index (WI)* |
|---|---|---|---|---|
| | 1 | Waterflooding | 50 | +0.97 |
| | 2 | Waterflooding | 17.25 | +0.97 |
| A10 | 3 | Waterflooding | $\Delta P$ = 70 mbar | -0.15 |
| | 4 | Waterflooding (*) | 16.7 | -0.15 |
| | 5 | Waterflooding | 3.5 | -0.15 |
| | 6 | Centrifugation | - | -0.15 |
| | 7 | Waterflooding (*) | 8.36 | +0.86 |
| | 8 | Waterflooding | 133.5 | +0.86 |
| | 9 | Waterflooding | 133.5 | 0 |
| Berea | 10 | Waterflooding (*) | 8.36 | 0 |
| | 11 | Waterflooding (*) | 3 | 0 |
| | 12 | Waterflooding | 0.64 | 0 |
| | 13 | Centrifugation | - | 0 |
| Lagrave | 14 | Centrifugation | - | Int. Wet. |

(*) These experiments have been carried out under gammaray monitoring.

## Rocks

All these experiments have been performed on rock samples which are well known for their homogeneity. They have been verified by X ray before any measurements. They are described as follows :

- Aerolith 10 (A 10), a synthetic aluminium silicate. This material has been already used in many studies related to wettability or waterflooding problems (Hamon *et al.*, 1986; Hamon, 1988). The A 10 characteristics are detailed in Table 2
- Berea sandstone (characteristics are detailed in Table 3)
- Reservoir core sample (oil wet reservoir).

**TABLE 2 : Aerolith 10 characteristics**

| | *Exp. n° 1 to n° 4* | *Exp. n° 5* |
|---|---|---|
| Length (cm) | 25 | 31.4 |
| Section (cm2) | 45.36 | 19.63 |
| Porosity (%) | 43.5 | 43.5 |
| Gas permeability | 4900 | - |

**TABLE 3 : Berea sandstone characteristics**

| | *Exp. n° 7-8* | *Exp. n° 9-11* | *Exp. n° 12* |
|---|---|---|---|
| Length (cm) | 25.94 | 28.3 | 27.7 |
| Section (cm2) | 19.63 | 19.63 | 19.56 |
| Porosity (%) | 22.9 | 22.7 | 22.5 |
| Gas permeability | 1140 | 1140 | 1140 |

## Fluids

Three different kind of fluids have been used :

- neutral oil (Marcol 52)
- recombined brine (20 g/l of NaCl + 20 g/l of $CaCl_2$)
- stock tank oil (from Lagrave field) for the wettability restoration.

A neutral oil has been used for the waterfloodings to have the most constant wettability index during the experiments. This is especially important in case of low rate waterfloodings. More details on fluid properties are given in Table 4.

**TABLE 4 : Fluids characteristics**

| | *Density* | *Viscosity (cP)* | *Temperature (°C)* |
|---|---|---|---|
| Marcol 52 | 0.827 | 11.5 | 20 |
| Brine | 1.023 | 1 | 20 |
| Stock tank oil | 0.807 | 2.02 | 70 |

## EXPERIMENTAL RESULTS AND DISCUSSION.

### Waterfloodings on Aerolith10.

The main results are summarized in Tables 5 (water wet experiments) and 6 (intermediate wet experiments).

**TABLE 5 : Aerolith 10 - Water wet experiments**

| *Experiments n° :* | | *1* | *2* |
|---|---|---|---|
| Permeability at $S_w = S_{wi}$ | md | 4000 | 4000 |
| at $S_w = 1 - S_{or}$ | md | 2000 | 1600 |
| Initial water saturation | % | 9.7 | 11.5 |
| Residual oil saturation | % | 15.5 | 19.3 |
| Oil recovery at breakthrough. | % OOIP | 56 | 62.6 |
| Pore volume injected | | 0.51 | 0.56 |
| Final oil recovery | % OOIP | 82.8 | 78.2 |
| Pore volume injected | | 29 | 4.8 |
| Injection rate | $cm^3/h$ | 50 | 17.25 |
| Front velocity | cm/day. | 81.1 | 30.25 |

**TABLE 6 : Aerolith 10 - Intermediate wet experiments**

| *Experiments n° :* | | 3 | 4 | 5 |
|---|---|---|---|---|
| Permeability at $S_W = S_{WI}$ | md | 4000 | 3900 | No ΔP |
| at $S_W = 1 - S_{or}$ | md | 1280 | 950 | recorded |
| Initial water saturation | % | 10.3 | 12.8 | 19.4 |
| Residual oil saturation | % | 18.1 | 36.7 (1) | 26.9 (1) |
| | | | 21.8 (2) | 22 (2) |
| Oil recovery at B.T. | % OOIP | 45.1 | 51.6 | 53.7 |
| Pore volume injected | | 0.41 | 0.45 | 0.44 |
| Final oil recovery | % OOIP | 79.8 | 57.9 (1) | 66.6 (1) |
| | | | 75 (2) | 72.7 (2) |
| Pore volume injected | | 31 | 6 (1) | 4.2 (1) |
| Injection rate | $cm^3/h$ | | 16.7 (1) | 3.5 (1) |
| | | | 600 (2) | 60 (2) |
| Pressure drop | mbar | 70 | | |
| Front velocity | cm/day | | 93.2 (1) | 7.9 (1) |
| | | | 50733 (2) | 124.5 (2) |

(1) : at the end of low rate waterflooding

(2) : after several increases of the injection rate

However, some details are surprising, as the value of $k_{rw}(S_{orw}) = 0.4$ obtained in the water wet case which seems to be high. In particular, it is higher than the value obtained in the intermediate wettability case ($k_{rw}(S_{orw}) = 0.235$). This result is unexpected, and is not completely explained yet. However, we can note that the remaining oil saturations are almost identical in both cases, and these values are also in good agreement with the centrifuge ones.

At the end of experiments n° 2 (water wet case) and n° 4 (intermediate wet case), the injection rate has been increased step by step, and the pressure drop (ΔP) has been recorded (Table 7).

**TABLE 7 : Aerolith 10 - Injection rate increases.**

| | *Q* *($cm^3/h$)* | *ΔP* *(mbar)* | *Sorw* *(%)* | *Krw* |
|---|---|---|---|---|
| | 17.25 | 1.8 | 19.4 | 0.37 |
| Water wet | 35 | 3.6 | 19.4 | 0.37 |
| | 70 | 7.5 | 19.4 | 0.36 |
| | 140 | 13.5 | 19.4 | 0.40 |
| | 16.7 | 28 | 36.7 | 0.023 |
| Intermediate | 35 | 40 | 36 | 0.034 |
| wet | 135 | 55 | 30.3 | 0.096 |
| | 378 | 80 | 27 | 0.185 |
| | 600 | 100 | 21.8 | 0.235 |

In the water wet case, any additional oil productions appeared with the injection rate increases. This observation indicates that the residual oil saturation has been already reached at the end of the previous experiment. The relative permeabilities and capillary pressure curves are thus completely determined.

On the other hand, for the intermediate wet case, the remaining oil saturation decreases from 36.7 % to 21.8% when the flow rate is increased from 16.7 $cm^3/h$ to 600 $cm^3/h$ step by step. It is then important to know if this variation comes from a diminution of end effects (oil retention near the outlet face of the core, laboratory artefact) or from a real decrease in the residual oil saturation along the total core length.

Several experiments have been carried out with local saturation measurements using gammaray attenuation technique. The water saturation profiles (Figure 1) are relatively homogeneous along the core sample at the end of experiments, even if some end effects on the outlet and inlet faces can be observed. Also, the profiles shown are the ones obtained during experiment n° 4, but before any injection rate increases. The influence of these end effects will decrease when the injection rate increases.

Consequently, the average water saturation can be assumed to be equal to the true water saturation ($S_w$) without making a major error. The points ($S_w$, $\Delta P$) can be plotted on the centrifuge imbibition capillary pressure curve determined on a separate plug and using the same fluids (Figure 2). These two curves are in a good agreement. By analogy with the gas/oil system (drainage process), it means that, for a given flow rate (or pressure drop), the remaining oil saturation is limited by capillary forces, which are in equilibrium with the viscous forces ($P_c = \Delta P$) when the flow is stabilized. At this saturation, the oil relative permeability ($k_{ro}$) is not zero as it is generally assumed. To obtain the real residual oil saturation, the pressure drop should be increased to compensate the capillary forces which can be important around SOR in intermediate wettability case.

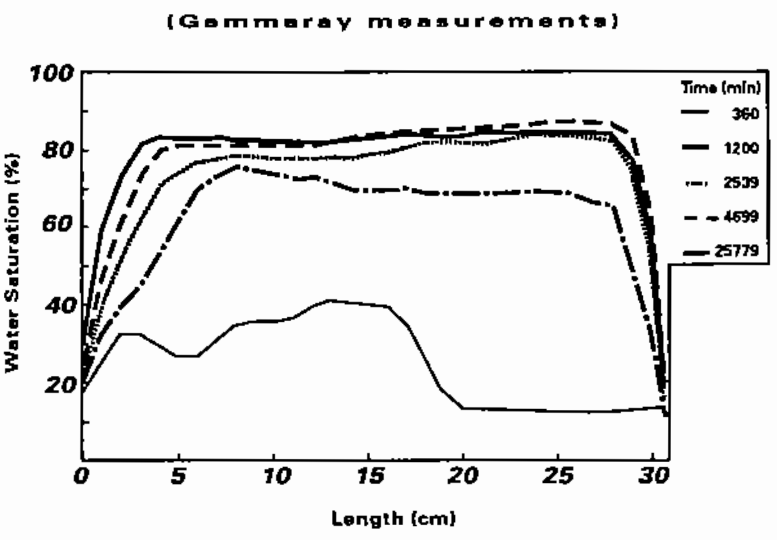


Figure 1 : Water saturation profiles on A 10

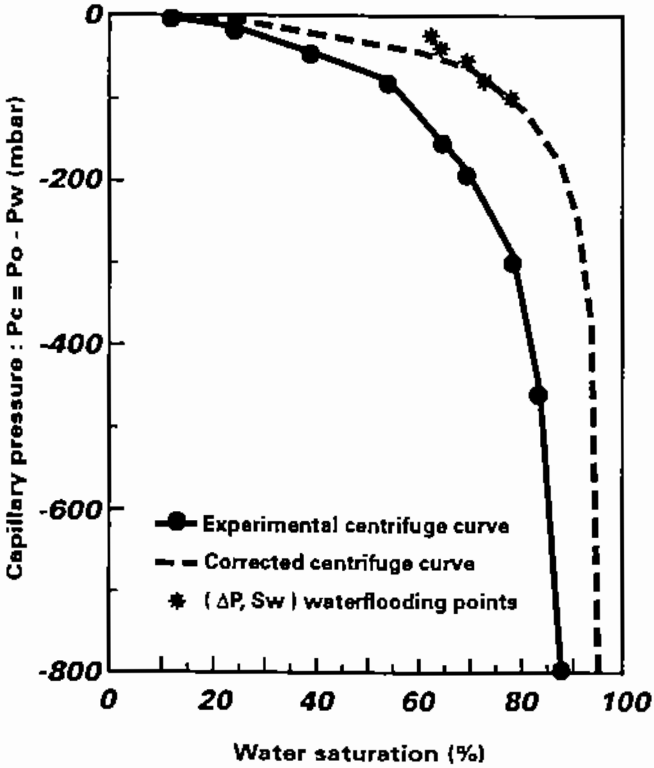


**Figure 2 : Capillary pressure curves on an intermediate wet Aerolith 10 sample**

The centrifugation techniques allow us to apply a larger pressure gradient than the one obtained by floodings. Therefore, the remaining oil saturation obtained at the end of the centrifuge experiments can be assumed to be representative of the residual oil saturation. This is especially important for permeable media. In such cases, the maximal pressure gradient possible by waterflooding is not big enough to reach the SOR. The ΔP = 100 mbar obtained at the maximal injection rate on A 10 is quite small in front of ΔP = 800 mbar obtained by centrifugation.

## Waterfloodings on Berea sandstone

The main results are summarized in Tables 8 (water wet experiments) and 9 (intermediate wet experiments).

**TABLE 8 : Berea sandstone - Water wet experiments**

| *Experiments n° :* | | *7* | *8* |
|---|---|---|---|
| Permeability at $S_W = 100\%$ | md | 800 | 817 |
| at $S_W = S_{wi}$ | md | 880 | 1036 |
| at $S_W = 1 - S_{or}$ | md | 37.5 | 50.5 |
| Initial water saturation | % | 14.4 | 15.4 |
| Residual oil saturation | % | 42.9 | 42.7 |
| Oil recovery at breakthrough | % | 49.8 | 49.5 |
| Pore volume injected | | 0.45 | 0.42 |
| Final oil recovery | % | 49.9 | 50 |
| Pore volume injected | | 3.4 | 9.6 |
| Injection rate | $cm^3/h$ | 8.36 | 133.5 |
| Front velocity | cm/day | 105 | 1693.7 |

The follows classical behaviors have been observed :

- for a given wettability, the bigger the injection rate is, the sooner the breakthrough happens, and the lower the recovery at breakthrough,
- for a given flow rate, the breakthough happens later in the case of intermediate wettability than in case of water wettability

For the water wet case, the results are identical for both flow rates :

- same recovery at breakthrough,
- same final recovery,

- a single phase production (water) after the breakthrough (even after increase of the flow rate),
- same water relative permeability at SOR

**TABLE 9 : Berea - Intermediate wet experiments**

| *Experiments n° :* | *9* | *10* | *11* | *12* |
|---|---|---|---|---|
| Permeability (md) | | | | |
| at $S_W$ = 100% | 800 | 630 | 600 | - |
| at $S_W = S_{WI}$ | 880 | 750 | 710 | 850 |
| at $S_W = 1 - S_{or}$ | 290 | 275 | 169 | — |
| Initial water sat. (%) | 17.75 | 13.5 | 17.1 | 19.6 |
| Residual oil sat. (%) | 21.2 | 25.9 (1) | 29.8 (1) | 31.6 (1) |
| | | 23 (2) | 24.8 (2) | 23.5 (2) |
| Oil recovery at B.T. (%) | 40.6 | 50.1 | 55.6 | 60.7 |
| Pore volume injected | 0.34 | 0.43 | 0.44 | 0.53 |
| Final oil recovery (%) | 74.2 | 70 (1) | 64 (1) | 60.7 (1) |
| | | 73.4 (2) | 70.4 (2) | 70.8 (2) |
| Pore volume injected | 64.6 | 6.3 (1) | 2.2 (1) | 1.8 (1) |
| Injection rate ($cm^3$/h) | 133.5 | 8.36 (1) | 3 (1) | 0.64 (1) |
| | | 300 (2) | 600 (2) | |
| Front velocity (cm/day) | 1177.8 | 74.3 (1) | 30.6 (1) | 7.15 (1) |
| | | 2544 (2) | 5586 (2) | |

(1) : at the end of the low rate waterflooding
(2) : after several increases of the injection rate

So, as for the A 10, it is shown on Berea that the two phase flow properties are well determined by classical waterflooding in the water wet case.

At the end of experiments n° 10 and n° 11 (intermediate wet cases), the injection rate has been increased with recording the pressure drop ($\Delta P$). The results obtained are described in Table 10.

The remaining oil saturation decreases 2.9 % in the first case and 5.2 % in the second case when the injection rate increases.

**TABLE 10 : Berea - Injection rate increases.**

| | *Q* *($cm^3/h$)* | *ΔP* *(mbar)* | *Sorw* *(%)* | *Krw* |
|---|---|---|---|---|
| | 8.36 | - | 25.9 | - |
| Water wet | 300 | 450 | 23 | 0.356 |
| Intermediate wet | 3 | 47.5 | 30 | 0.037 |
| | 6 | 70 | 29 | 0.050 |
| | 18 | 72.5 | 27 | 0.144 |
| | 200 | - | 25.7 | - |
| | 600 | - | 24.8 | - |

(Gammaray measurements)

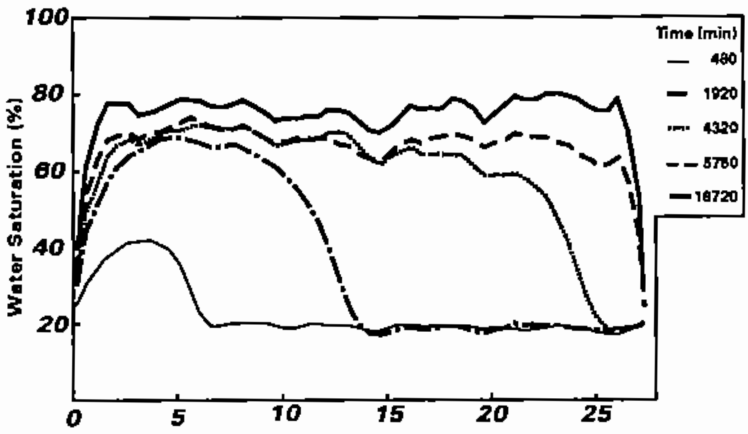


**Figure 3 : Water saturation profiles on Berea**

The water saturation profiles obtained by gammayray show that end effects do not have a major influence (Figure 3). So, as previously done and with the same remarks, the points ($S_W$, $\Delta P$) obtained at the end of waterflooding after each increases of the injection rate have been plotted on the centrifuge imbibition $P_C$ curve (Figure 4). These points are in good agreement with this $P_C$ curve, and the conclusions made for the A 10 can be repeated in this case.

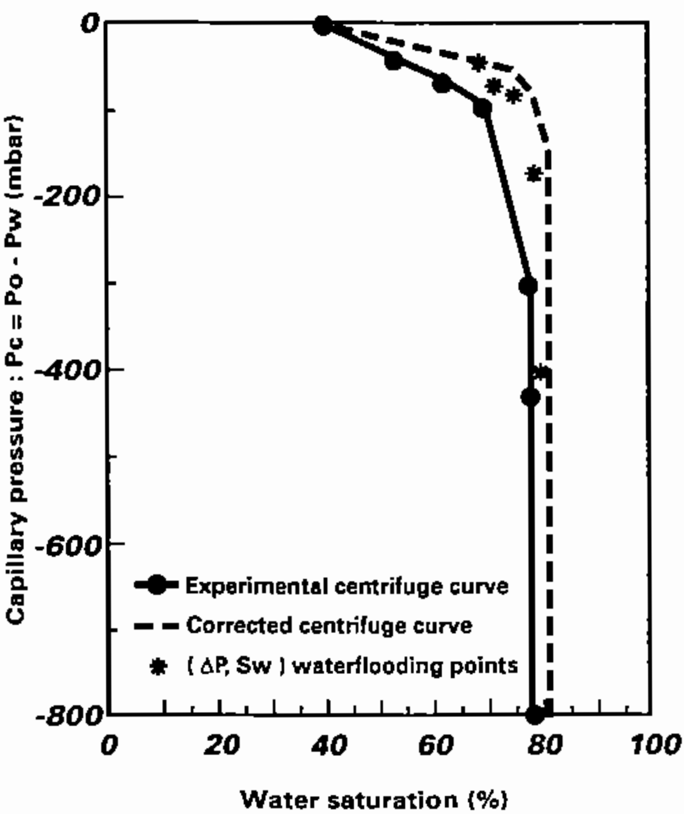


**Figure 4 : Capillary pressure curves on an intermediate wet Berea sample**

In addition, a comparison between water saturation profiles obtained by gammaray measurements and the ones resulting of the waterflooding numerical interpretation has been made on Berea (Figures 3 and 5). The relative permeabilities used for the simulations are given in Figure 6. The experimental profiles are well reproduced numerically :

- indentical front shape before the breakthrough
- after breakthrough, the profiles are translated. The end effects are not very pronounced, which explain the fairly flat shape of the capillary pressure curve in this saturation range.

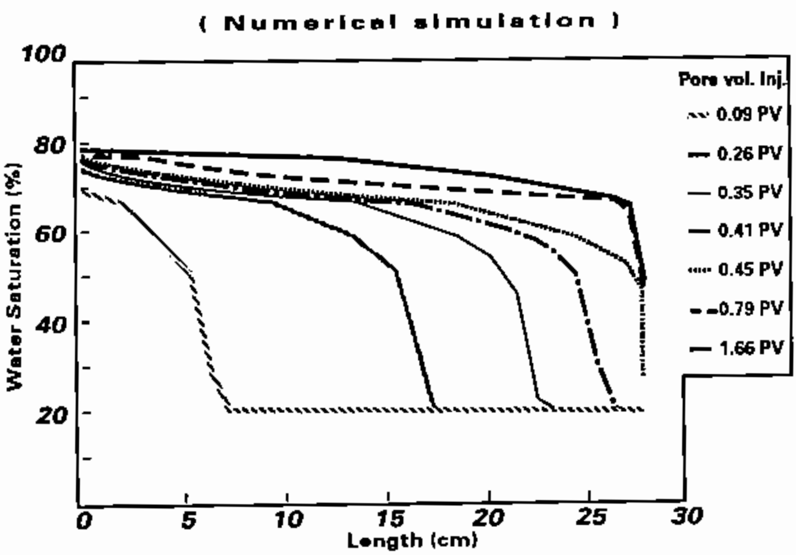


Figure 5 : Water saturation profiles Berea sample

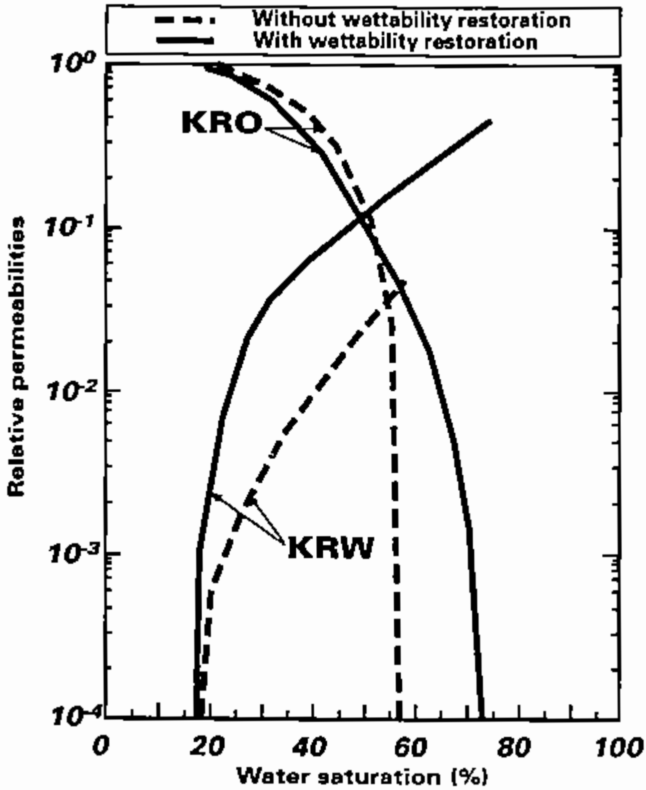


**Figure 6 : Water/oil permeabilities for Berea**

Only the inlet face phenomena are not numerically reproduced. However, on the contrary of the outlet end effects which are controlled by capillary forces, the inlet face effects can be assumed to be an experimental artefact.

**Comparison between $P_C$ simulation and $P_C$ centrifugation on a reservoir core sample (from Lagrave field).**

The experimental waterflooding history matching allows to determine the imbibition capillary pressure. But, the validity of this procedure is not well established yet. Hence, we compared the capillary pressure curves obtained by numerical interpretations and the ones obtained by centrifugation.

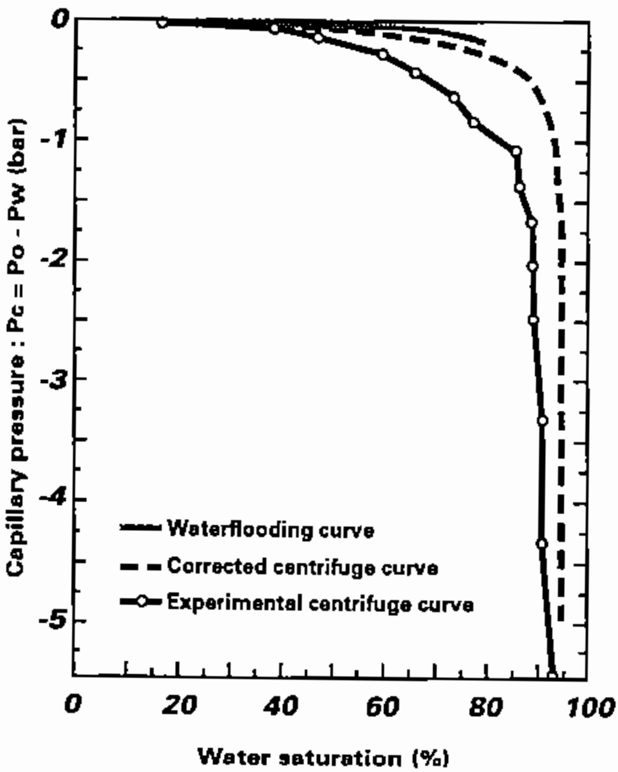


Figure 7 : Capillary pressure curves comparison on a Lagrave core sample

This experiment has been carried out on a Lagrave core sample, well known for its oil wet behavior. The general agreement (Figure 7) is good, but it is difficult to do a finer comparison. The investigation area of these two methods are quite different. For the waterfloodings interpretation, the capillary forces are not very important (several 10 of mbar). The centrifugation techniques are not very precise in this capillary pressure range which correspond to very low rotation speeds. However, the point $S_W(P_C=0)$ and the general trend are identical : important saturation variation for a small capillary pressure variation in the common part.

Some improvements in this new technique are needed, and some works are still going on.

## CONCLUSIONS

A good consistency between all waterfloodings and centrifugation experiments has been obtained on these two rocks. Based on these experimental results, we can conclude that for a permeable intermediate wet media :

- the end effects are controlled mainly by capillary forces
- the remaining oil saturation (ROS) at the end of a waterflooding depends on the pressure gradient and the cumulative volume of water injected
- the coreflood ROS is generally higher than the centrifuge ROS which is supposed to be the more representative of the true residual oil saturation. The difference is in the range of 5 to 10 %. It means that the relative permeabilities have to be determined until the centrifuge ROS value.

It is then recommended to associate waterflooding and centrifugation experiments to get a better two phase flow properties determination.

## REFERENCES.


AMOTT E. (1959). Observations relating to the wettability of porous rock. *Pet. Trans. AIME 216*, pg 156-162

CUIEC L. (1991). Evaluation of reservoir wettability and its effects on oil recovery.In *Interfacial Phenomena in Petroleum Recovery, Surfactant science series, Vol 36,* N. Morrow (ed.), Marcel Dekker, New York , Chap. 9

DELCLAUD J. (1974). Etude du déplacement de l'huile par le gaz. *Revue de l'Institut Français du Pétrole*, Juillet-Août 1974, pg. 473-505

DELCLAUD J., ROCHON J. and NECTOUX A. (1987). Investigation of gas/oil relative permeabilities : high permeability oil reservoir application. SPE 16966, presented at the 62nd Annual Fall Meeting, September 27-30, 1987, Dallas, Texas.

FORBES P. (1991). A simple and accurate method for converting centrifuge data into drainage and imbibition capillary pressure curves. SCA 9107, presented at the 5th Annual Technical Conference, August 20-22, 1991, San Antonio, Texas.

GLOTIN G., Genet J. and Klein P. (1990). Computation of drainage and imbibition capillary pressure curves from centrifuge experiments. SPE 20502, presented at the 65th Annual Fall Meeting, September 23-26, 1990, New Orleans, Louisiana.

HAMON G. and VIDAL J. (1986). Scaling-up the capillary imbibition process from laboratory experiments on homogeneous samples. SPE 15852, presented at the SPE European Petroleum Conference, October 20-22, 1986, London, England.

HAMON G. (1988). Oil/water gravity drainage mechanisms in oil-wet fractured reservoirs. SPE 18366, presented at the SPE European Petroleum Conference, October 16-19, 1988, London, England.

LABASTIE A., GUY M., DELCLAUD J. and IFFLY R. (1980). Effect of flow rate and wettability on water-oil relative permeabilities and capillary pressure. SPE 9236, presented at the 55th Annual Fall Meeting, September 21-24, 1980, Dallas, Texas.

MORROW N.R. et MUNGAN N. (1971). Mouillabilité et capillarité en milieux poreux. *Revue de l'Institut Français du Pétrole,* Juillet-Août 1971, pg. 629-650

O'MEARA, HIRASAKI and ROHAN (1988). Centrifuge measurements of capillary pressure - part I - Outflow boundary conditions. SPE 18296, October 2-5, 1988, Houston, Texas.

VIDAL J. (1990). Determination of characteristics of Ekofisk formations by forced and spontaneous expérimental waterfloodings. Presented at "Third North Sea Chalk Symposium", June 11-12, 1990, Copenhagen, Denmark.

WOOD A.R., WILCOX T.C., MacDONALD D.G., FLYNN J.J. and ANGERT P.F. (1991). Determining effective residual oil saturation for mixed wettability reservoirs : Endicott field, Alaska. SPE 22903, presented at the 66th Annual Fall Meeting, October 6-9, 1991, Dallas, Texas.

## APPENDIX A - WETTABILITY RESTORATION PROCEDURE

Before any experiments, the wettability index evolution has been studied as a function of aging time on Aerolith 10 (Figure 8) and Berea sandstone (Figure 9). This wettability index has been determined by the classical Amott-IFP method (Amott, 1959 and Cuiec, 1991) and is varying as following :

- for A 10 : from +0.97 (water wet) originally, to -0.39 (oil wet) after an aging period of 4 weeks
- for Berea : from +0.86 (water wet) originally, to -0.74 (oil wet) after an aging period of 4 weeks

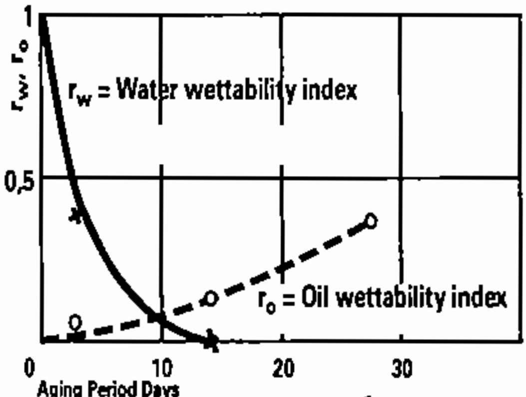


**Figure 8 : Wettability index as a function of aging time on A 10**

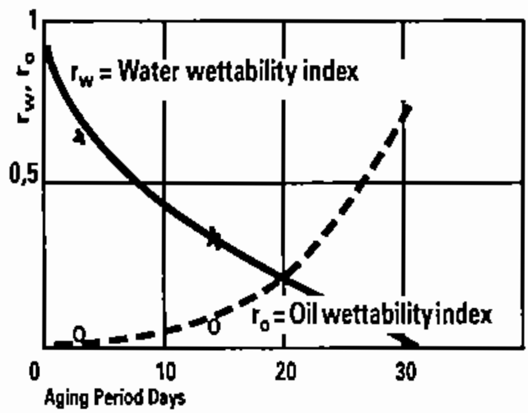


**Figure 9 : Wettability index as a function of time on Berea.**

Stabilisation is not obtained even after a four weeks aging period. However, some works made by L. Cuiec (1991) showed that the wettability index is generaly stable after a 7 or 10 days aging period in case of reservoir rocks (even if it is not an absolute general rule). It is the standard duration used for wettability restoration before corefloods in our laboratories.

For this study, experiments have been carried out first on the original stage of both media (water wet), and secondly after a two weeks aging period for Aerolith 10 (WI = -0.15) and a three weeks aging period for Berea (WI = 0).

## APPENDIX B - CENTRIFUGE CAPILLARY PRESSURE DETERMINATION

The forced drainage and forced imbibition capillary curves can be determined from centrifuge experiments. However, in case of productions reading while centrifuging, the experimental curves have to be corrected from the acceleration gradient. Several techniques has been already developed, and the purpose of this appendix is not to add another one or to comment them. Two different models have been used during these works. The first one has been studied and developed by G. Glotin *et al.* (1990). The second one, developed by P. Forbes (1991) is more recent and also simplier.

Just one remark should be pointed out. Before any numerical interpretation, the Hassler-Brunner condition should be verified. It means that the water saturation at outlet face must be equal to one and the capillary pressure must be equal to zero. Several authors have quantified this boundary by the Bound number ($N_B$) :

$$N_B = \Delta\rho\, \omega^2\, r\, r_p/\sigma$$

where :

| | | |
|---|---|---|
| $\Delta\rho$ | : | density difference |
| $\omega$ | : | rotation speed |
| $r$ | : | distance with the rotation axe |
| $r_p$ | : | radius of the largest pore |
| $\sigma$ | : | interfacial tension |

Several limit values have been fixed (O'Meara *et al.*, 1991) :

| | | |
|---|---|---|
| Stegemeier | : | $N_B > 0.5$ |
| Melrose | : | $N_B = 0.57$ |
| Bretherton | : | $N_B = 0.84$ |
| Wunderlich | : | $N_B < 0.73$ |

Then, it is preferable to verify that $N_B$ is around 0.5, specially when the rotation speed exceed 10 000 rpm.