# IMPROVED RELATIVE PERMEABILITY MEASURED BY INJECTING OIL FOLLOWING A BRINE INJECTION TEST

Moreno,R.B.Z.L.*; Schiozer,D.J*; Kikuchi,M.M** and Bonet,E.J.*
*Unicamp, **Petrobras

*This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Toronto, Canada, 21-25 August, 2005*

## ABSTRACT

The objective of this work was to broaden the saturation range over which relative permeabilities were measured by following unsteady-state water injection tests with unsteady-state oil injection tests. Results are shown for a formation that presents negligible kr hysterisis. Capillary end-effects were negligible because long (25cm) samples and high flow rates were used while testing. X-ray scans of samples showed consistent saturation throughout each core after steady-state conditions were achieved. Constant rate tests (1) for high and medium absolute permeability rocks and (2) with low, medium and high viscosity oil were performed. Some cores were also treated to change wettability in order to study differences between hydrophilic and hydrophobic media. As a final verification, a steady-state test with oil injection was performed. The steady state test results were calculated directly using Darcy's law, while the unsteady-state results were calculated using the traditional JBN method. Comparison for the results with different rock properties, different oil viscosities and different wettabilities allowed observing the enlarged investigated region. These results permitted also to observe the advantages of the additional oil injection tests. Tests are treated as water and oil injection rather than imbibition and drainage in order to not misunderstand tests in hydrophilic and hydrophobic samples.

## INTRODUCTION

Relative permeability (kr) is of paramount importance in predicting reservoir performance. Different methods are proposed for measuring these rock characteristics. The most common measurement techniques employed are transient, steady state, and centrifuge methods [1,3,5,7,8,11,12,14,17]. Variations in these methods also appear in the literature, such as stationary phase and drainage techniques [8,13]. The most experimentally expeditious method is the transient method with water injection (transient imbibition). The drawback of this method, aside from computational complexity, is that under certain conditions, the range of saturation over which relative permeability is characterized is diminutive. To increase the investigated region, one can continue the unsteady-state relative permeability test by switching from water to oil injection, thereby enlarging the measured saturation region.

This paper focuses on two-phase kr and fractional flow curves. An analysis is made for the increased saturation range of interest that is achieved by performing oil injection after the water injection [13]. Tests are treated as water and oil injection rather than imbibition and drainage in order to not misunderstand tests in hydrophilic and hydrophobic samples. To observe the same investigated region by the oil injection, the results from transient tests are compared to the steady-state results. The steady-state test is performed at constant total injection rate and by increasing the water rate. Capillary pressure effects were disregarded since high rates and long core samples were used [3,5]. Moreover, the tests were planned and executed in order to avoid distortions due to gravity and limits of applicability for capillary number [4,16,18]. The experimental results confirm that under predicted conditions the investigated range is considerably increased by continuing the test with oil injection.

## EXPERIMENTAL SET-UP AND TESTS

The tests consisted mainly in transient displacement at constant rate by injecting water or oil. Additional comparisons were made from transient tests and steady-state measurements. The steady test consisted of simultaneously injecting water and oil in increasing proportions, maintaining constant the total rate. The experimental set-up is presented in Figure 1.

As shown in the sketch: pumps, transducers, scale, and measuring separator are the main components to measure injection and production rates and differential pressures. Saturation profiles were measured via X-ray. Botucatu sandstone was used as the porous media in these tests. Gomes *et al.* [6] provide petrographical and petrophysical descriptions of this sandstone. Figure 2 shows water fractional flow for the Botucatu formation from imbibition and drainage tests. Results did not exhibit significant hysterisis.

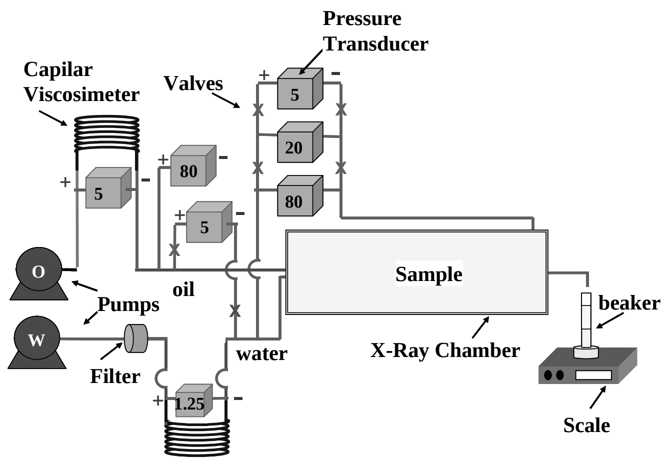


**Figure 1 - Components for the testing apparatus.**

The tests were run in longitudinal cylindrical samples. The water was doped with 65000 ppm sodium iodine, appropriate for x-ray scanning. The tests were performed to cover different rock and fluid conditions, involving medium and high permeability rocks. Both hydrophilic and hydrophobic rocks were tested, with low, medium and high viscosity oil. The original hydrophilic rock was transformed to a hydrophobic rock by treating with Quilon (trademark of Du Pont Company) chrome complexes that changed the rock wettability [2]. After the treatment, the avidity of the hydrophobic rock was found to be less than one percent of the avidity of the previously hydrophilic rock. Summary of porous media properties and tests characteristics are in Table 1.

## MATHEMATICAL CALCULATIONS

The JBN [9] method was used to calculate kr from unsteady-state tests, while the steady-state relative permeabilities were calculated using Darcy´s law. Figure 3 shows a typical fractional flow curve. With water injection, one can measure kr after breakthrough. This region is investigated by drawing a tangent to this curve from the irreducible water saturation shown in the curve. With oil injection one measures the low portion of the fractional flow curve from a tangent obtained from the residual oil saturation. There is a non-measurable region, between the two tangent points. The detailed methodology to calculate the relative permeabilities are described elsewhere [3,8,9,10,15].

## RESULTS AND DISCUSSION

A **range** parameter was arbitrarily created to calculate the ratio of investigated region during oil injection and investigated region during water injection. This range provides a comparison between range of saturation change with oil and water injection. When **range** is greater than one, the saturation range over which relative permeabilities are determined is greater during oil injection than during water injection. Mathematically, **range** is expressed by Eq. (1):

$$range = \frac{1 - S_{ofd} - S_{wi}}{1 - S_{or} - S_{wfe}} \tag{1}$$

A summary of 12 reported tests is presented in Table 1. The first ten tests are an unsteady oil injection following unsteady water injection, while the last two follow steady-state oil-water injection. Six tests were performed in hydrophilic media and the other six, in hydrophobic rocks. Six were performed with 108 cP oil, five with 1.5 cP oil and one with 12 cP oil.

As could be expected, observing the last column of Table 1, the 1.5 cP oil presents a range equal or greater than one, implying that oil injection investigates the same or greater region than a water injection test. The 108 cP oil, with one exception (test 8), presents a range much smaller than one, implying that the region investigated by the oil injection is much smaller than water injection. This shows that the greatest gain from implementing an oil injection test is achieved when the oil viscosity is low.

Although there are exceptions, comparing test 5 and 6 (same range permeabilities, same viscosities) and comparing tests 7 and 9 (same range permeabilities and same viscosities) one can conclude that hydrophobic rocks present greater investigative region with oil injection. Figures 6 through 11 show relative permeability and fractional flow results. The effective permeability used to calculate kr is the effective oil permeability at initial water saturation. Normalized water saturation, defined by Eq. (2), was used.

$$S_w^* = \frac{S_w - S_{wi}}{1 - S_{wi} - S_{or}} \tag{2}$$

With this definition and data from Table 1, one has enough information to normalize saturation according to a different scheme. Likewise, as absolute permeabilities are also listed, one can normalize permeabilities according to a different base if desired.

When only a water injection test is performed, the final curve is obtained connecting the initial point (fw=0; kro(swi)=1, krw=0) with the breakthrough values.

In Figures 4 and 5, Tests 2 and 7 are compared, with and without performing the oil injection. Two extreme situations were chosen. In Figure 4, there is no difference by doing the additional oil injection. In fact, the curves are superimposed and it is not possible to distinguish between cases. In Figure 5, significant differences are observed with injection of oil. A low viscosity oil was used in the test of Figure 4, and a high viscosity oil in the test of Figure 5. Figures 10 and 11 compare steady-state results with those from subsequent oil injection tests. Steady-state results show the complete curve with the oil injection while the oil injection shows a smaller investigated region. In the same investigated region the oil relative permeability does not present significant differences, but due to the low relative water permeability, small differences in this parameter cause important differences in the water fractional flow values.

## CONCLUSIONS

- Transient and steady state two-phase kr tests were successfully performed under different rock and fluid conditions. Water injection and oil injection tests were compared.
- Oil injection increases the measured region for relative permeability.
- Final water saturation with oil injection is normally greater than the initial water saturation. The difference is mainly due to the desaturation process.
- Higher oil viscosity increases the investigated region by oil injection.
- Hydrophobic rocks present greater investigated range, by oil injection, when compared with hydrophilic rocks.
- The magnitude of absolute permeability does not show a clear trend in the investigated range.
- Compared results with and without oil injection test can show large discrepancies in high viscosity oil and insignificant differences with low viscosity oil.
- Comparison between results from transient oil injection and steady state tests gives similar values for oil relative permeability.

## REFERENCES

1 Amyx, J. W., Bass Jr., D. M. & Whiting, R. L.: *Petroleum Reservoir Engineering Physical Properties*, McGraw-Hill Book Company, USA, 1960, 610 p.
2 Anderson, W. G.. “Wettability Literature Survey – Part 5: The Effects of Wettability on Relative Permeability”. *JPT*, p 1453-1468, November 1987.
3 Batycky, J. P. et alli.. “Interpreting Relative Permeability and Wettability from Unsteady-State Displacement Measurements”. *SPE Journal*, p 296-308, June 1981.
4 Fulcher JR., R. A.; Ertekin, T., Stahl, C. D.. “Effect of Capillary Number and Its Constituents on Two-Phase Relative Permeability Curves”. *SPE Journal*, 1985, p 249-260.
5 Geffen, T. M.; Owens, W. W.; Parrish, D. R., Morese, R. A.. “Experimental Investigation of Factors Affecting Laboratory Relative Permeability Measurements”. *Petroleum Transactions, AIME*, Vol. 192, p 99-110, 1951.
6 Gomes, J.A.T., Tibana, P. and Corrêa, A.C. , Caracterização Petrofisica e Petrográfica dos Arenitos Berea e Botucatu, Conexpo Arpel, Rio de Janeiro, 1996.
7 Heaviside, J.; Black, C. J. J., Berry, J. F.. “Fundamentals of Relative Permeability: Experimental and Theoretical Considerations”. SPE 12173, p 1-17. October 5-8, 1983.
8 Honarpour, M.; Koederitz, L. & Harvey, A. H.. *Relative Permeability of Petroleum Reservoirs*, CRC Press Inc.,USA, 2000. 143 p.
9 Johnson, E.F., Bossler, D.P. AND Naumann, V.O., “Calculation of Relative Permeability from Displacement Experiments”, *Petroleum Transactions, AIME*, (216),370-372, 1959
10 Jones, S.C. and Rozzelle, W.O., “Graphical Techniques for Determining Relative Permeability from Displacements Experiments”, JPT, 807-817, May 1978.
11 Munkvold, F. R., Torsaeter, O.. “Relative Permeability from Centrifuge and Unsteady State Experiments”. SPE 21103. 1990, p 1-13.
12 Potter, G. F., Groves, D. R.. “Displacements, Saturations, and Porosity Profiles from Steady-State Permeability Measurements”. SPE 19679, 1989, p 485-498.

13 Qadder, S.; Brigham, W. E., Castanier, L. M.. "Techniques to Handle Limitations in Dynamic kr Measurements". ekofisk.stanford.edu/supria/publications/public/tr128.pdf

14 Rapoport, L. A. & Leas, W. J.. "Relative Permeability to Liquid in Liquid-Gas Systems". Petroleum Transactions, AIME, Vol. 192, p 83-98. 1951.

15 Shafer, J. L.; Braun, E. M.; Wood III, A. C., Wooten, J. M.. "Obtaining Relative Permeability Data using a Combination of Steady-State and Unsteady-State Corefloods". Paper No. 9009, Presented at the SCA Conference. 1990.

16 Santos, R. L. A.; Bedrikovetsky, P. & Holleben, C. R.. "Optimal Design and Planning for Laboratory Corefloods". 50th Latin American and Caribbean Petroleum Engineering Conference and Exhibition in Brazil, p 1-11. August 30 to September 3, 1997.

17 Urkedal, H., Ebeltoft, E., Nordvedt, J.E. and Watson, A.T.. "A New Design of Steady-State Type Experiments for Simultaneous Estimation of Two-Phase Flow Functions". SPE Reservoir Eval. & Eng., Vol. 3, No. 3, June 2000, pp. 230-238.

18 Virnovsky, G. A.; Skjaeveland, S. M., Surdal, J.. "Steady-State Relative Permeability Measurements Corrected for Capillary Effects". SPE 30541. 1995, pp. 85-95.


Acknowledgments: *To Petrobras for the financial support to this project and to Luiz B. Pompeo Netto and to Leandro A. Fernandes for their great assistance with the experiments.*

**Table 1- Basic samples properties and test characteristics**

| Test No. | Poros. fr | Permeability | | | | Saturation | | | Oil Visc. cp | Wett. | Before Drain. | Front Saturations | | Ratio drai/ embeb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Gas mD | Water mD | Oil (Swi) mD | Water (Sor) mD | Water Swi | Sw drain. fr. | Sor | | | | Swfe | Sofd | |
| **1** | 0.27 | 2483 | 2785 | 1832 | 606 | 0.274 | 0.330 | 0.246 | 108 | OW | US | 0.336 | 0.589 | 0.328 |
| **2** | 0.29 | 3582 | 3763 | 2649 | 1137 | 0.190 | 0.180 | 0.348 | 108 | OW | US | 0.263 | 0.802 | 0.020 |
| **3** | 0.29 | 6193 | 6199 | 5178 | 713 | 0.150 | 0.160 | 0.325 | 108 | WW | US | 0.176 | 0.701 | 0.298 |
| **4** | 0.29 | 7059 | 6847 | 7473 | 1248 | 0.172 | 0.160 | 0.261 | 108 | WW | US | 0.174 | 0.695 | 0.236 |
| **5** | 0.30 | 7924 | 6341 | 7328 | 4404 | 0.128 | 0.380 | 0.124 | 1.5 | WW | US | 0.498 | 0.500 | 0.983 |
| **6** | 0.28 | 6929 | 8369 | 6970 | 2545 | 0.243 | 0.278 | 0.223 | 1.5 | OW | US | 0.680 | 0.595 | 1.672 |
| **7** | 0.26 | 329 | 328 | 328 | 57 | 0.216 | 0.245 | 0.250 | 1.5 | OW | US | 0.530 | 0.431 | 1.605 |
| **8** | 0.18 | 108 | 134 | 94 | 2.85 | 0.089 | 0.279 | 0.291 | 108 | WW | US | 0.405 | 0.549 | 1.191 |
| **9** | 0.17 | 144 | 136 | 248 | 7.45 | 0.163 | 0.300 | 0.120 | 1.5 | WW | US | 0.528 | 0.486 | 0.997 |
| **10** | 0.26 | 653 | 642 | 317 | 15 | 0.219 | 0.130 | 0.460 | 12 | WW | US | 0.503 | 0.701 | 2.150 |
| **11** | 0.27 | 6527 | 7060 | 5137 | 682 | 0.206 | 0.420 | 0.193 | 108 | OW | SS | 0.530 | 0.613 | 0.653 |
| **12** | 0.27 | 6595 | 5537 | 2919 | 184 | 0.336 | 0.390 | 0.135 | 1.5 | OW | SS | 0.735 | 0.418 | 1.892 |

(*)OW: hydrophobic ; WW: hydrophilic (**)US: unsteady; SS: steady

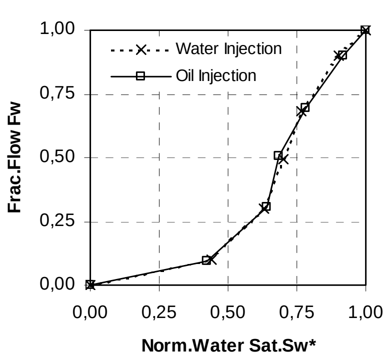


**Figure 2 Water fractional flow curves for imbibition and drainage**

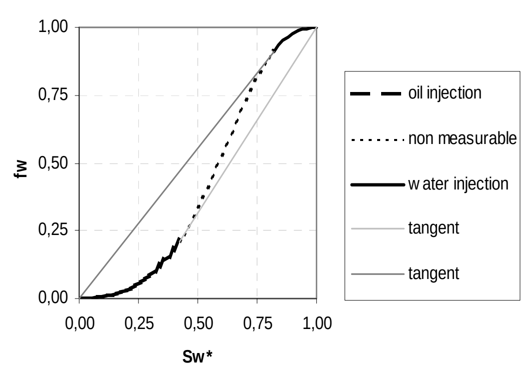


**Figure 3 Investigated regions in displacement tests**

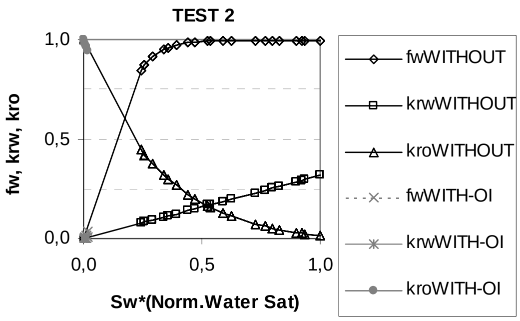


Figure 4 Comparison results with and without oil injection (no differences)

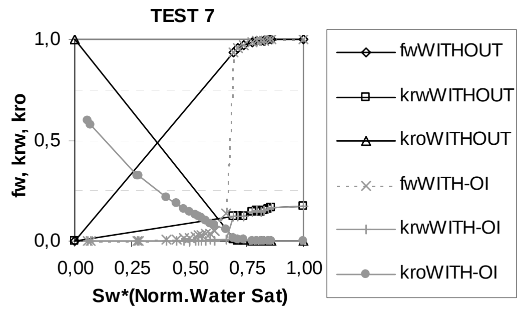


Figure 5 Comparison results with and without oil injection (great differences)

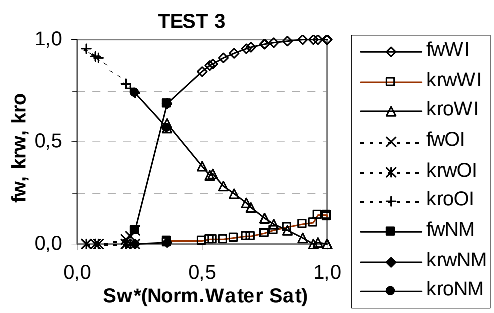


**Figure 6 – Test 3 WI-water injection,OI=oil injection,NM=non-measurable**

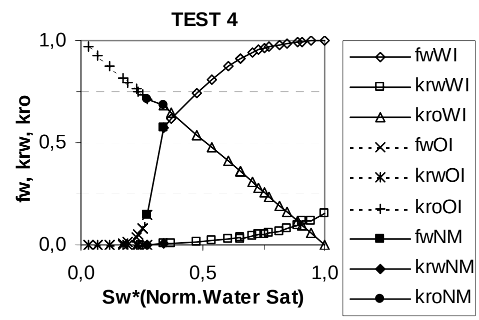


**Figure 7 – Test 4 WI-water injection,OI=oil injection,NM=non-measurable**

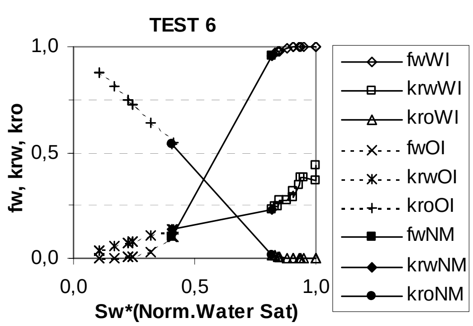


**Figure 8- Test 6 WI-water injection,OI=oil injection,NM=non-measurable**

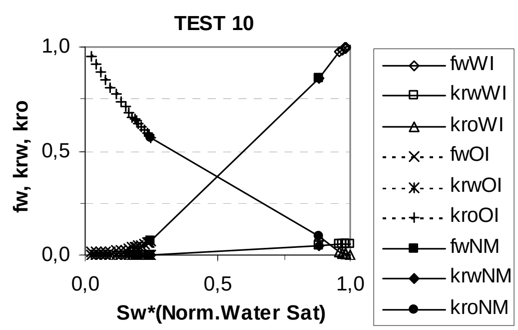


**Figure 9 – Test 10 WI-water injection,OI=oil injection,NM=non-measurable**

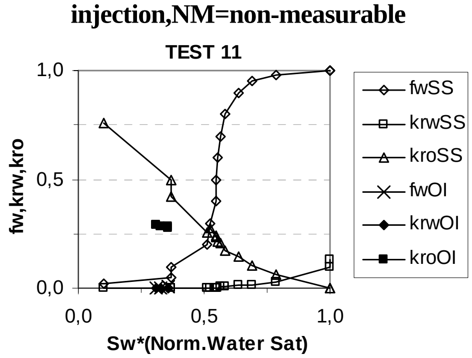


**Figure 10 – Test 11 SS-steady-state,OI=oil injection,**

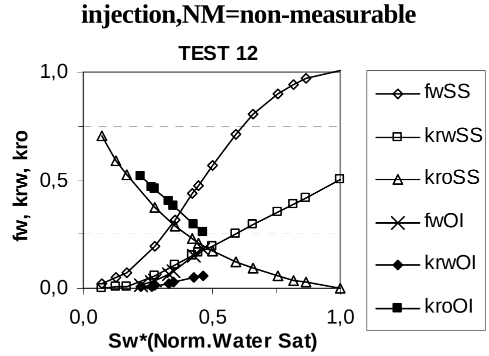


**Figure 11 Test 12 SS-steady-state,OI=oil injection**