# PERFORMANCE AND NUMERICAL INTERPRETATION OF GAS DRAINAGE CORE TESTS UNDER SECONDARY AND TERTIARY CONDITIONS

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**Abstract**
This paper introduces a new method to determine the relative permeabilities of three-phase system -gas-oil-water-flowing in a porous medium.
Gas injections in porous media are performed in multiple conditions of initial saturations. The recovered quantities of fluid are recorded versus time
A model is applied to simulate a gas injection process and to describe oil, water and gas production in the case of each experiment. Required input to the model are the values of the relative permeabilities for the three phases, written in the form of tables as functions of water and gas saturation. The relative permeability tables are modified until a good fit is found between the experimental and the calculated productions. These relative permeability values are then considered as the relative permeabilities that actually correspond to the displacements. Using these tables allows to well describe the multiple phenomena encountered during a gas injection, even the behavior of an immobile phase obtained in two-phase conditions and displaced subsequently by gas.

## Introduction
Three-phase relative permeabilities are frequently measured using the steady-state method [1]. This method consists in injecting the three phases together (or at least two, the third one being immobile) through the porous medium. The flowrates of the fluids are imposed and the pressure drop between the inlet and the outlet of the core is measured. The relative pemeabilities are then calculated for each fluid using Darcy's law. This method is time consuming and it is well known that the relative permeabilities obtained in this way rarely represent the behavior of the fluids during a displacement [2,3], especially when interfacial phenomena take place as it is the case for a nonspreading oil. In this case, meniscus formation occurs when oil is displaced by gas but cannot occur if the two fluids, oil and gas, flow in separate channels in the porous medium as it happens with the steady-state method.
Therefore, the best way to determine the actual relative permeabilities is to calculate them under the same conditions as those that prevail during a displacement.
The aim of this study is to validate a method to determine the relative permeabilities corresponding to gas injections performed in the laboratory.

The adopted procedure consists of the following steps:

1. A simplified technique is used to evaluate quickly approximate values of the relative permeabilities in the two-phase and the three-phase cases and to give the curvature of the isoperms;

2. With the preliminary tables as input, the cumulative oil, water and gas productions are obtained from the simulations;

3. When compared, the experimental and calculated productions curves point out the time step, the mean saturation, then the relative permeabilities values to be corrected;

4. After several simulation-correction cycles, a good fit is obtained between the experimental and the simulated production curves.

**Experiments**

**Porous Medium.** The two porous media used are a Fontainebleau sandstone and a Vosges sandstone between 40 and 70 cm in length, and with a relatively high permeability, $K \approx 3x10^{-8}$ $cm^2$(3000 md).

**Fluids.** One set of fluids has been selected with respect to their surface tensions in order to ensure a positive spreading coefficient. The fluids are a brine with 25 g/l Ba Cl2, with a viscosity, $\mu_w$= 1.1 mPa.s, Soltrol 170 as the oil phase, with a viscosity, $\mu_o$= 2.72 mPa.s and nitrogen as the gas phase, with a viscosity, $\mu_g$= 1.8 x$10^{-2}$ mPa.s.

**Experimental Device.**The equipment consists of a pair of pumps injecting one of the two liquids at a constant rate, the gas being injected at a constant pressure. A separator in line with a gasometer is located at the outlet of the core. This device monitors the volume of liquids and gas produced when the fluids are put in place or during the final displacement. Before being injected, the gas is humidified by flowing through a cell containing the water phase.

**Experimental Procedure.**

*Two-Phase Tests.* The core is evacuated then saturated with brine and, oil is finally injected to irreducible water saturation, Swi. The displacement of the oil in place is studied by performing a water imbibition or a gas drainage. The displacement of oil by water is generally followed by a gas injection.

*Three-Phase Tests.* After a two-phase displacement by gas, a steady-state flood is performed by injecting simultaneously oil and water with a given ratio of flowrates. At the end of such a test, the saturations inside the porous medium are, low for the trapped gas, and, high enough for the liquids to make them both mobilized by the final gas injection

**Experimental results**

*Two-Phase Displacements*

a) Fontainebleau sandstone

• The displacement of oil with an irreducible water saturation (Swi=0.24 PV) by a water injection leads to the establishment of a residual oil saturation (Sor= 0.32). The recovery curves shown in Figure 1 is characteristic of a piston-like displacement. The corresponding saturation variation appears in Figure 2 on the oil-water basis of the ternary diagram.

• The other two-phase displacement studied is a gas injection starting from a saturation state such as only the oil phase is mobile (Swi=0.23,Sgt=0.22PV). The production of oil and the total production are shown in Figure 1. It can be noticed that the gas appears very quickly (Break-through at $10^3$ s) due to its high mobility. It is shown in Figure 2 (Two- Phase Oil/Gas) that a small amount of the irreducible water is recovered (Final Swi=0.20PV).

b) Vosges sandstone. The two experiments performed with this sandstone are gas injection in the two extreme cases: oil plus irreducible water, Swi and water plus residual oil, Sor. It is shown in Figure 3 that the mobility of gas leads to an early B.T. especially in presence of a continuous oil phase. On the other hand, in both cases, part of the initially immobile phase is recovered. The saturation variation during these two displacements is shown in Figure 4.

*Three-Phase Displacements*

The three-phase displacements of a mobile oil and a mobile water are performed with various conditions of saturations. These various conditions make it possible to sweep different zones of the ternary diagram of saturations (Figure 2).

The production history ( Example in Figure 5 ) depends greatly on the initial saturation conditions:

• at first, oil and water are produced with flowrates certainly roughly proportional to their saturation, showing a similar behavior against the gas phase.

• very early (around 10 minutes), that corresponding to a low jump of the gas saturation, gas appears at the outlet end of the core and the three fluids are produced together;

• gas injection is continued till the production of the liquids is not noticeable.

On the ternary diagram (Figure 2) the saturations are displayed at the beginning and at the end of the experiments as well as the path of the saturation taken during these experiments. The saturations are calculated for each experiment from the quantity of fluid recovered versus time. These experimental mean values correspond to the values found later by simulation in each grid and versus time.

**Relative Permeability Calculation**

If, during a gas injection, several phases are mobile as it is the case with a high saturation of oil and water, or when recovery of a part of a residual oil saturation together with the water in place occurs, a three-phase model is required. Among the input data are the relative permeabilities for the three fluids: water, gas and oil in the form of tables. The relative permeabilities are expressed as functions of two saturations: Sw and Sg.

The tables are determined using the following informations which are detailed hereafter:

• the two-phase relative permeability values deduced from the two-phase displacements are known;

• other values can be deduced directly from the three-phase displacement themselves using a new method of calculation (pseudo steady-state);

• the curvature of the isoperm curves can be deduced directly from the production history.

**Establishment of the Preliminary Tables**

*Two-Phase Relative Permeabilities*

When only oil is mobile, should it be displaced by gas or water, the history matching of the displacements is possible following a conventional way. It is obtained by an automatic procedure [4]( Simulation curves in Figure 1 together with the experimental ones ).

The curves corresponding to the two-phase relative permeabilities used are shown in Figure 6.

It can be seen that the residual oil saturation is lower after a gas injection than after a waterflood (Sorg = 0.15, Sorw = 0.29). This difference highlights the advantage of a gas injection process, compared to a water injection.

The oil relative permeability values are displayed in Figure 7 on the two-phase paths already shown in Figure 2.

*Approximate Method of Calculation (Pseudo steady-state method)*

The three-phase experiments to be simulated can be used directly to evaluate quickly the relative permeabilities using the following hypothesis: during a gas injection, it has been observed that the saturation front traveling along the porous medium has a high velocity but leads to a low saturation drop (in the range of 10% PV) as can usually be deduced from a fractional flow curve. The final gas saturation at the end of the experiment can be great but total recovery needs a long time to be achieved; during this period of time, the saturation variation versus time and along the length of the porous medium is a very slow phenomenon; it can be assumed that the gas flowrate and the pressure measured at a given time correspond to a stable state of flow. Relative permeability to gas is then calculated and its saturation evaluated from the volume of the liquids recovered. Because the conditions of this calculation are very similar to those established during a steady-state method, the proposed method, although applied to a displacement, has been called *pseudo steady-state method*. In spite of the fact that the flow of the liquids is due to the gas flow, this calculation is also applied for the two liquids, assuming also that their saturation is uniform during the long period of time after the gas front has left the porous medium.

*Curvature of the Isoperm Curves*

If we observe the production curves obtained in the case of the displacement of water + Sor by gas in the Vosges sandstone, the following results can be pointed out:

• the production of the residual oil is important but takes place after a long period of time as shown in Figure 3;

• this is depicted by the ternary diagram in Figure 4, where it can be seen that the path taken during this displacement is made of a first linear part at Sor = const. and by a curved part following a decreasing oil saturation;

• this shows that, because the relative permeability of oil is zero at the beginning of the displacement (the linear part of the saturation path), the isoperm Kro = 0 follows certainly roughly the linear part of the saturation path. During this period of time, only water is displaced by gas and the water saturation decreases;

• the fact that oil production starts when the gas saturation reaches 0.25 PV shows that this saturation corresponds to an increasing relative permeability to oil. That means that the isoperm Kro = 0 is curved and lies on the left side of the path taken during this displacement (Figure 4);

• the same argument can be applied to the displacement of an irreducible water by gas but with a very slight recovery ;

• the general curvature of the isoperms is then known and helps in the establishement of the tables.

This conclusion found for the Vosges sandstone with displacements in the area of residual or irreducible saturation is certainly also valid for Fontainebleau sandstone and it can be assumed that the path of the three-phase displacement (Figure 2) lay between the isoperms Kro = 0 and Krw = 0. The passageway thus created is certainly the forced way for all the three-phase displacements.

The values of the relative permeabilities found from the two-phase displacements and from the pseudo steady-state method applied to the three-phase experiments make it possible to deduce the isoperm curves and finally to build the first relative permeability tables:

• for water, the isoperms are assumed to be practically linear as suggested by the isoperm Krw = 0 represented in Figure 4. The relative permeability to water is assumed to depend only on the water saturation, at least in the range of the values measured;

• for gas, the values of the two-phase relative permeabilities are known in a large range of gas saturation but only in a region of the diagram corresponding to a low water saturation, along Swi = 0.25. From pseudo-steady-state measurements gas relative permeability is found to depend almost only on gas saturation. Apart from that region it is impossible to guess the curvature of the isoperm in the whole triangle. The first tables will be then established, assuming that Krg is a function of only Sg. These values will eventually be modified during the various simulations;

• for oil, the results cover a larger area in the ternary diagram: the two-phase diplacements along two lines, Swi = 0.25 and Sg = 0.0 and the three-phase values given by the pseudo steady-state method, that is along three lines corresponding to the experiments, between Sg = 0.08 and Sg = 0.68. The isoperm Kro = 0 is known and the other isoperms are drawn between all these points with the same curvature (Figure 7).

The relative permeability table for oil is then deduced from the isoperm curves. From these asumptions, the tables can be written versus the two saturations:

• water saturation (lines of the tables) covering more than the saturation variation found during the three-phase displacements;

• gas saturation (columns of the tables) from 0. to 65%PV;

At first a saturation table which shows the correlation between So and the two other ones is established (Table 1). The various paths taken during the experiments can be easily followed and they determine the boxes of use for each two-phase or three-phase displacement. These boxes are filled up with the relative permeability values coming from the isoperm curves established earlier.

**Adjustement of the Tables**

A few simulations are performed and their results lead us to modify the tables as follows:

• the experimental production curves and those coming from the simulation are drawn in the same figure (example for displacement D2, Figure 5);

• the parts of these curves where the fit is not good are located by the corresponding time. Figure 5 shows a small gap concerning the gas production at $t=10^3$s.

• this time gives the mean saturation of water and gas in the porous medium, through curves saturation vs. time established from the experimental data. Figure 8 shows that Sw= 0.30 and Sg= 0.24 for $t=10^3$s;

• these saturation values indicate a box on the Krg table, the corresponding Krg (here Krg= 0.009) has to be lowered as suggested by the production gap to be corrected;

**Results**

A good fit has been achieved between experimental and simulated production curves (Figure 5). The corresponding relative permeability tables are displayed on Table 2 and relative permeability values are plotted in Figures 9, 10 and 11 together with the relative permeabilities found previously (two-phase and pseudo steady-state values).

The following results have been obtained:

1. The three three-phase displacements can be simulated roughly with the same set of water relative permeabilities expressed as functions of the water saturation alone. However it appears that the water relative permeabilities take greater values when water is flowing together with oil than with gas (for two-phase displacements);

2. Oil relative permeabilities depend highly on both water and gas saturations. They recover their two-phase values when the water saturation is approaching its irreducible level. Calculated oil isoperms exhibit a strong curvature (Figure 7) showing that oil circulates more easily in presence of gas than in presence of water.

3. Two domains of variations of the gas relative permeability have been identified depending on the water saturation level (greater or less than 0.35 PV). In each of these two domains, the gas relative permeability is found to be function of the gas saturation alone. But for large values of water saturation (Sw>0.35, D3 in Figure 11), the gas relative permeability takes values lower than what was measured in presence of a small water saturation (Swi<0.35PV, D2 in Figure 11). This shows that the circulation of gas is made easier when gas is flowing with oil than with water and that the gas isoperms should be curved.

**Conclusions**

Three-phase displacements were conducted in porous media and numerically simulated. They led to the following conclusions regarding the three-phase relative permeabilities for gas, oil and water.

1. A new procedure, called pseudo steady-state method, for determining three-phase relative permeabilities has been validated. This method allows to calculate quickly approximate values of relative permeabilities to the three fluids directly from the production curves;

2. A new method to express three-phase relative permeabilities as functions of both the water and the gas saturations was proposed. Three-phase relative permeabilities are expressed in the form of tables in a discrete manner.

3. The relative permeabilities found present some interesting properties of the fluids. The water relative permeability is function of the water saturation alone, the gas relative permeabilities depend on gas saturation but two domains of water saturation can be distinguished. The relative permeability to oil is strongly dependent on both oil and water saturations and this leads to an important curvature of the oil isopem curves.

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**References**

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## Table 1 - Saturation Table

Sg=

| **0.0** | **0.08** | **0.24** | **0.30** | **0.35** | **0.40** | **0.45** | **0.50** | **0.55** | **0.60** | **0.65** | **Sw** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.84 | 0.76 | 0.60 | 0.54 | 0.49 | 0.44 | 0.39 | 0.34 | 0.29 | 0.24 | 0.19 | **0.16** |
| 0.80 | 0.72 | 0.56 | 0.50 | 0.45 | 0.40 | 0.35 | 0.30 | 0.25 | 0.20 | 0.15 | **0.20** |
| 0.75 | 0.67 | 0.51 | 0.45 | 0.40 | 0.35 | 0.30 | 0.25 | 0.20 | 0.15 | 0.10 | **0.25** |
| 0.70 | 0.62 | 0.46 | 0.40 | 0.35 | 0.30 | 0.25 | 0.20 | 0.15 | 0.10 | 0.05 | **0.30** |
| 0.65 | 0.57 | 0.41 | 0.35 | 0.30 | 0.25 | 0.20 | 0.15 | 0.10 | 0.05 | 0. | **0.35** |
| 0.60 | 0.52 | 0.36 | 0.30 | 0.25 | 0.20 | 0.15 | 0.10 | 0.05 | 0. | 0. | **0.40** |
| 0.55 | 0.47 | 0.31 | 0.25 | 0.20 | 0.15 | 0.10 | 0.05 | 0. | 0. | 0. | **0.45** |
| 0.50 | 0.42 | 0.26 | 0.20 | 0.15 | 0.10 | 0.05 | 0. | 0. | 0. | 0. | **0.50** |

## Table 2 - Relative Permeability Tables

### Water Relative Permeability - Krw

| **Sw:** | **0.16** | **0.20** | **0.25** | **0.30** | **0.35** | **0.40** | **0.45** | **0.50** |
|---|---|---|---|---|---|---|---|---|
| **Krw:** | 0. | 0.0001 | 0.001 | 0.0025 | 0.003 | 0.006 | 0.008 | 0.03 |

### Gas Relative Permeability - Krg

Sg=

| **0.0** | **0.08** | **0.24** | **0.30** | **0.35** | **0.40** | **0.45** | **0.50** | **0.55** | **0.60** | **0.65** | **Sw** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | .00012 | .009 | .02 | .04 | .07 | .08 | .1 | .1 | .1 | .1 | **0.16** |
| 0.0 | .00012 | .009 | .02 | .04 | .07 | .08 | .1 | .1 | .1 | | **0.20** |
| 0.0 | .00012 | .009 | .02 | .04 | .07 | .08 | | | | | **0.25** |
| 0.0 | .00012 | **.009** | .02 | .03 | .045 | .08 | | | | | **0.30** |
| 0.0 | .00012 | .009 | .015 | .03 | .045 | | | | | | **0.35** |
| 0.0 | .00012 | .0065 | .0065 | | | | | | | | **0.40** |
| 0.0 | .00012 | .0055 | | | | | | | | | **0.45** |
| 0.0 | .00012 | | | | | | | | | | **0.50** |

### Oil Relative Permeability - Kro

Sg=

| **0.0** | **0.08** | **0.24** | **0.30** | **0.35** | **0.40** | **0.45** | **0.50** | **0.55** | **0.60** | **0.65** | **Sw** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.60 | 0.38 | 0.15 | 0.10 | 0.07 | 0.05 | 0.03 | 0.02 | 0.01 | 0.003 | .00064 | **0.16** |
| 0.50 | 0.30 | 0.13 | 0.085 | 0.06 | 0.04 | 0.025 | 0.016 | 0.002 | 0.001 | 0.0 | **0.20** |
| 0.47 | 0.25 | 0.08 | 0.05 | 0.03 | 0.015 | 0.005 | 0.001 | 0. | 0. | 0. | **0.25** |
| 0.38 | 0.195 | 0.035 | 0.015 | 0.0056 | 0.0003 | 0. | 0. | 0. | 0. | 0. | **0.30** |
| 0.30 | 0.13 | 0.01 | 0.0032 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | **0.35** |
| 0.24 | 0.06 | 0.0007 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | **0.40** |
| 0.18 | 0.01 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | **0.45** |
| 0.14 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | **0.50** |

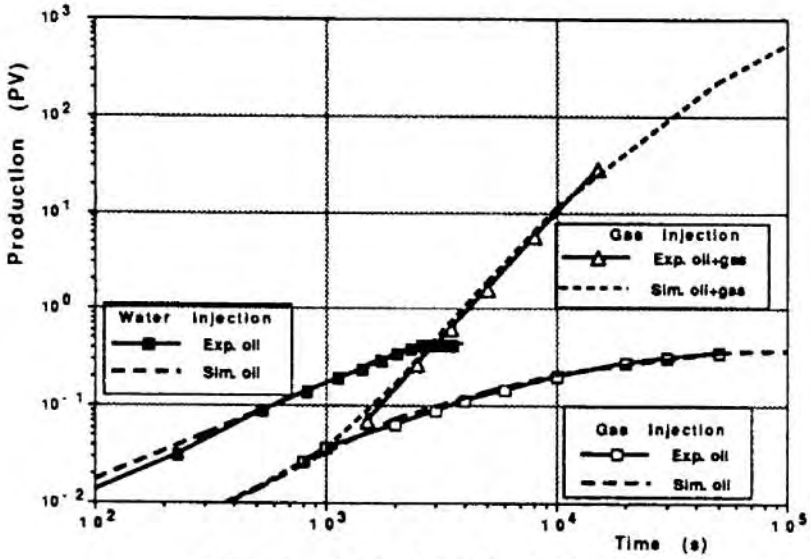


Figure 1 - Two-Phase Production
Experiments and Simulation

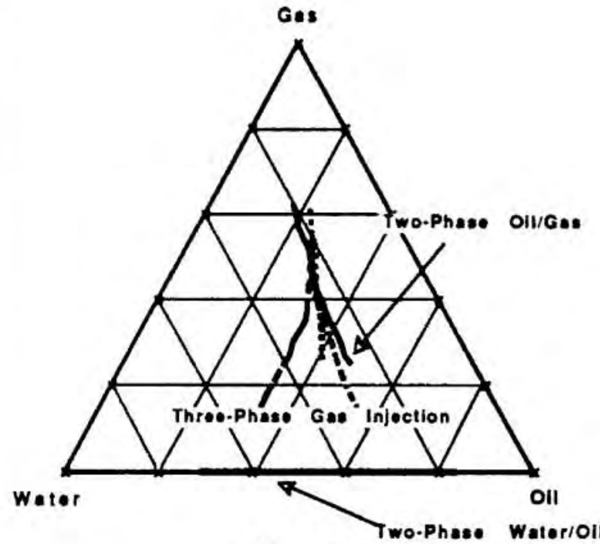


Figure 2
Two-Phase and Three-Phase Displacements

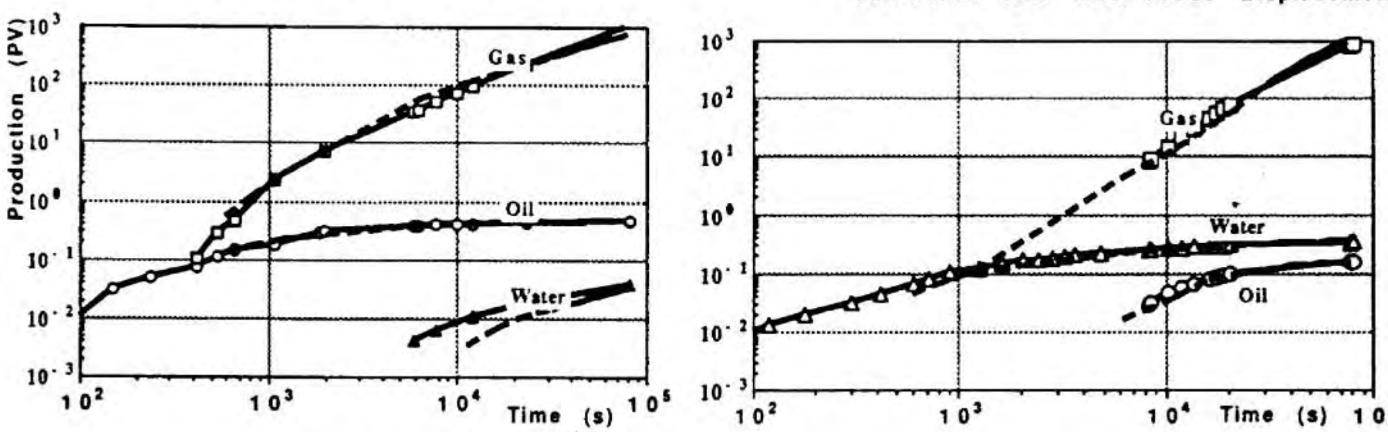


Figure 3 - Two-Phase Displacements Starting from Swi or Sor

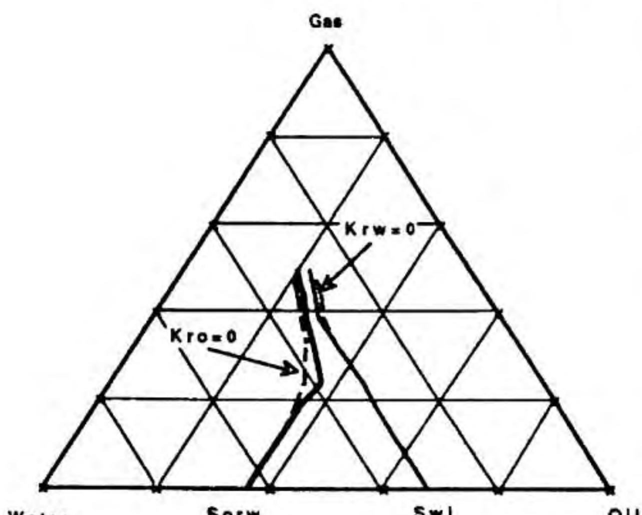


Figure 4 - Two-Phase Displacements
and Isoperm Curvature

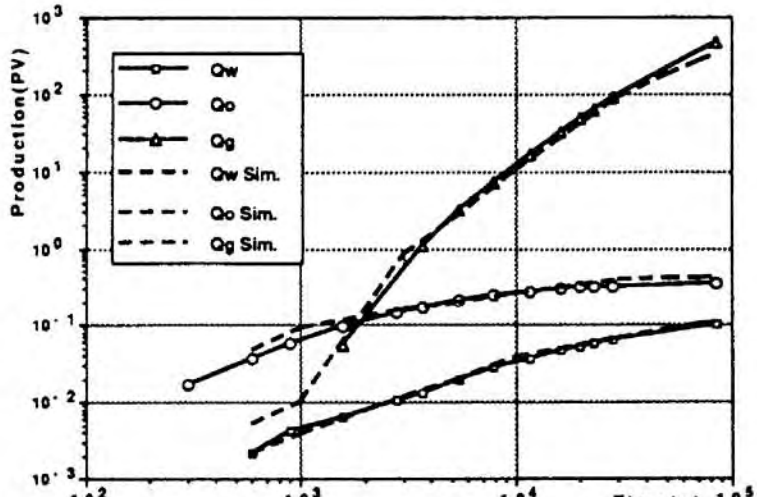


Figure 5 - Production curves
Three-Phase Displacement (Exp and Sim.)

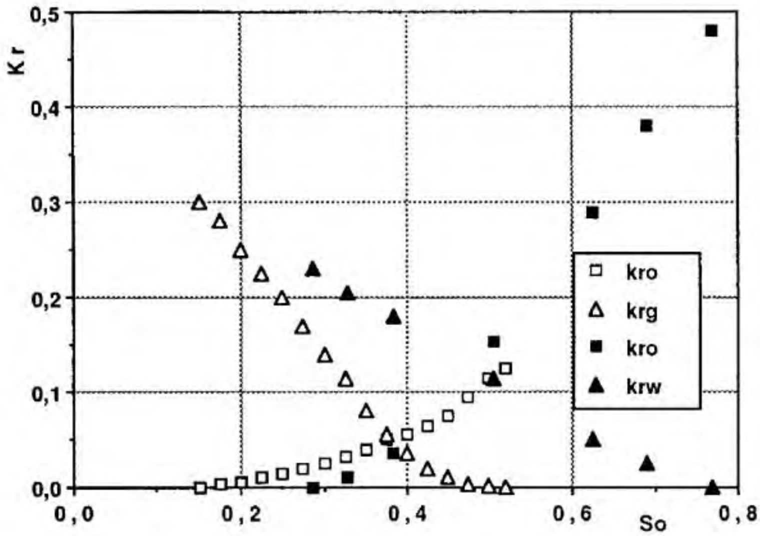


Figure 6
Two-Phase Relative Permeabilities
Simulated

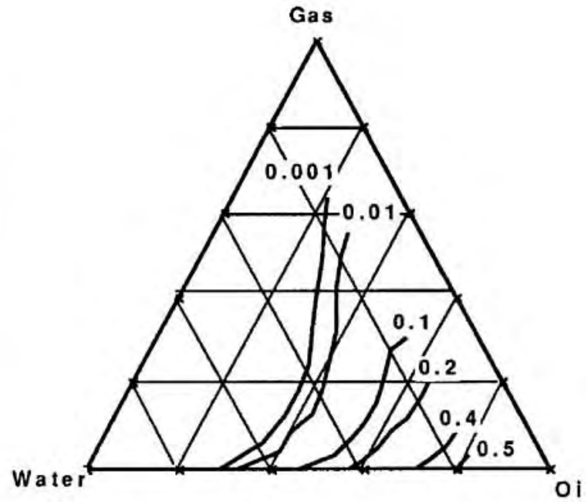


Figure 7 - Oil Relative Permeability
Two-Phase Values and Isoperm Curves

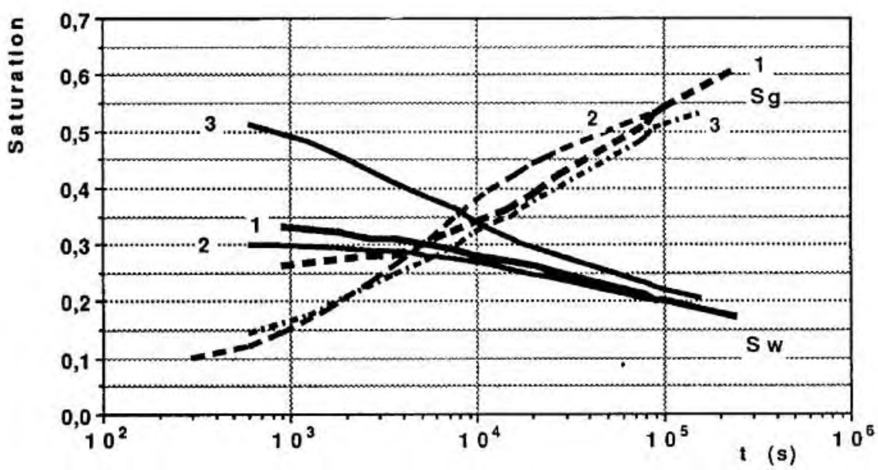


Figure 8 - Saturation vs Time during
the Three-Phase Displacements

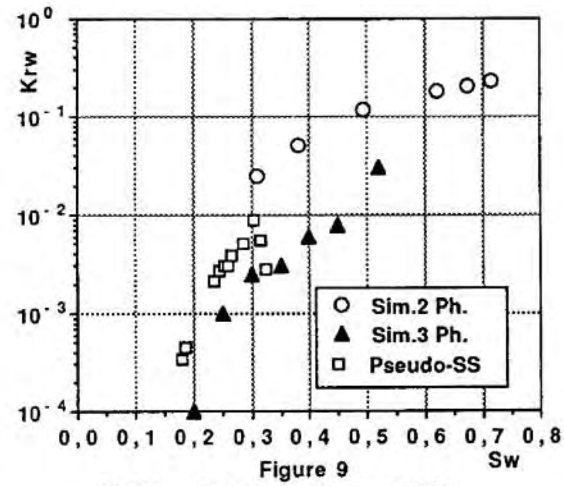


Figure 9
Water Relative Permeability

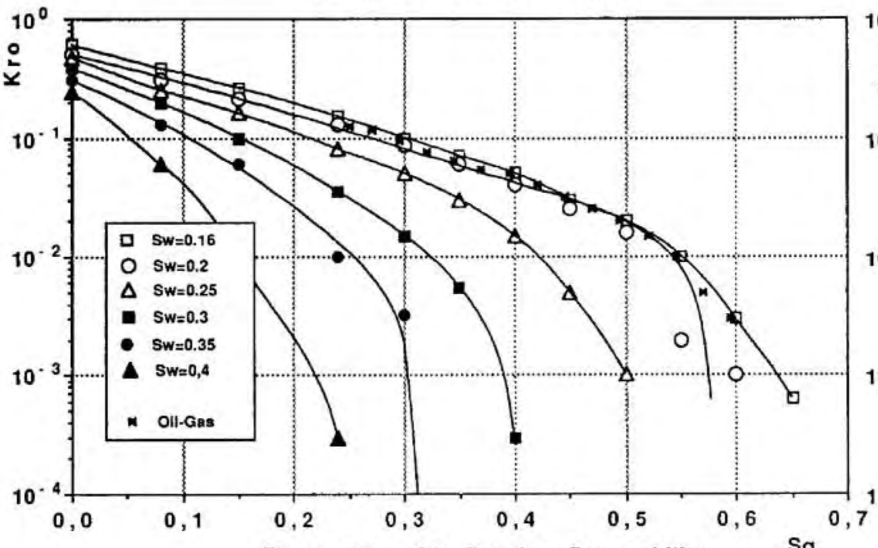


Figure 10 - Oil Relative Permeability

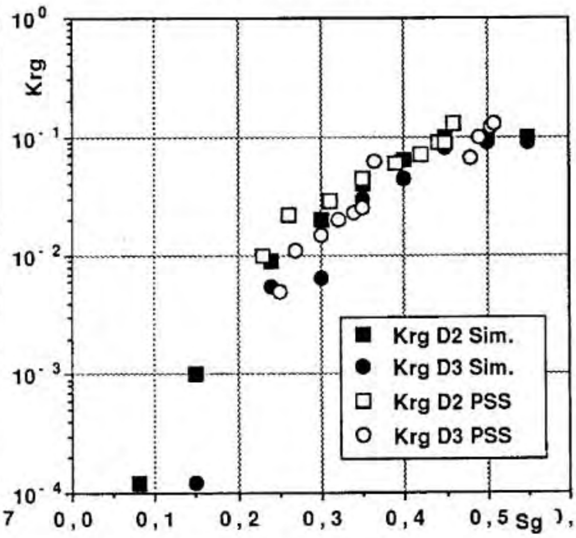


Figure 11 - Gas Relative Permeability

**Technical contributions:**

1. Performance and numerical interpretation of three-phase drainage tests with local saturation measurements by CT-scanning

2. Development of a new, predictive, applicable under any wettability conditions, methodology of estimation of three-phase relative permeabilities.