# Prediction of Gas Injection Performance for Heterogeneous Reservoirs

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# Disclaimer

# Abstract

This report outlines progress in the first 6 months of the second year of the DOE project 'Prediction of Gas Injection Performance for Heterogeneous Reservoirs' and contains a list of recent papers published.

# Contents



# 1 Executive Summary

This report describes research into gas injection processes in four main areas: laboratory experiments to measure three-phase relative permeability; network modeling to predict three-phase relative permeability; benchmark simulations of gas injection and waterflooding at the field scale; and the development of fast streamline techniques to study field-scale flow. The aim of the work is to achieve a comprehensive description of gas injection processes from the pore to the core to the reservoir scale. To this end, measurements of three-phase relative pemeability have been made and compared with predictions from pore scale modeling. At the field scale, streamline-based simulation has been extended to compositional displacements, providing a rapid method to predict oil recovery from gas injection.

# 2 Introduction

Gas injection in oil reservoirs offers huge potential for improved oil recovery. However, successful design of a gas injection process requires a detailed understanding of a variety of different significant processes, including the phase behavior of multicomponent mixtures and the approach to multi-contact miscibility in the reservoir, the flow of oil, water and gas underground, and the interaction of phase behavior, reservoir heterogeneity and gravity on overall performance at the field scale. This project attempts to tackle all these issues using a combination of theoretical, numerical and laboratory studies of gas injection, as described below.

# 3 Results and Discussion

We will now describe the research performed in two main areas: (1) three phase flow experiments; and (2) streamline-based simulation.

## 3.1 Three-Phase Flow Experiments

The effectiveness of water and gas in displacing oil depends greatly on the relative permeabilities of all the fluids. Experimental relative permeabilities are typically obtained indirectly from outflow data, which is then inverted assuming a specific type of displacement process. In contrast, we have developed techniques to quickly and directly obtain the relative permeabilities of all three phases.

To directly measure the relative permeability of a certain phase it is necessary to measure the phase's flux, the phase's pressure drop over a known length, and the phase's saturation over that length. For oil and water permeabilities, we use our CT scanner to measure the oil and water saturations versus position and time during gravity drainage. From this measurement we are also able to obtain the flux and the pressure drops. For gas relative permeability, we produce a core which in which the gas saturation varies along its length. We control the gas flux, measure the pressure drops using a manometer, and obtain the saturations by sectioning and drying the core. These techniques and the results for water-wet and oil-wet sand packs are elaborated as follows.

### 3.1.1 Oil and Water Relative Permeabilities

We have performed a series of three-phase gravity drainage experiments in water-wet and oil-wet sand packs. Using a CT scanner operating at two different energies, we are able to find the oil and water saturation of the core at a particular position and time. From the saturation information, we determine the fluxes and pressures and are thus able to determine the oil and water relative permeabilities.

The pack is homogeneous with a diameter of 7.5 cm and a length of 90 cm. For calibration purposes, the pack is scanned every 3 cm at two different X-ray energies, when it is dry, when it is fully saturated with water, and when it is fully saturated with oil. This represents 180 calibration scans for each experiment. Then the sand pack is fully saturated with water by injection from the bottom of the pack. Then oil is injected from the top until no further production of water is detected. At this stage the porous medium contains oil and connate water. Then water is injected from the bottom of the pack again until some desired initial oil saturation is reached. At this point, gas (nitrogen or air) is allowed to enter the top of the system, while water and oil drain out of the bottom under gravity. The pack is periodically scanned over a period of several weeks to record the saturation distribution.

We can compute the oil and water relative permeabilities from the known evolution of the saturation profile over time, if we know the capillary pressures. Capillary pressures are obtained from analog experiments performed on exactly the same type of packing with the same fluids. The fluids are left to drain for at least three weeks until capillary/gravity equilibrium is obtained. Then the sand is removed from the pack in 3 cm increments and the pore fluids are run through a gas chromatograph (GC). The GC provides an exceptionally accurate and sensitive measurement of saturation. From the measured saturation distribution, the oil/water, gas/oil and gas/water capillary pressures can be inferred.

For water-wet media, we performed experiments for different initial oil saturations before drainage and for three different oils hexane, n-octane and n-decane to represent systems with different spreading coefficients. Figure 1 shows the resulting relative permeabilities for n-octane and the water phase. We noticed a characteristic form of the oil relative permeabilities: for high oil saturations ($S_o > 0.2$), $k_{ro} \sim {S_o}^4$, while for low oil saturations, $k_{ro} \sim {S_o}^2$. This quadratic form of the relative permeability was shown to persist down to oil saturations as low as 0.02, and is consistent with the drainage of oil layers in the pore space (the theoretical developments will be described later). However, for the decane system, which is non-spreading, the layer drainage regime was not observed, oil was trapped and it is hypothesized that in this case oil layers did not form.

For oil-wet media our preliminary results show that the oil phase (octane) behaves similarly to the water phase in water-wet media, with oil saturations not dropping below $S_o = 0.04$. The water permeability drops off sharply near $S_w = 0.1$, consistent with the expectation of the absence of water layers, as water does not spread on oil. We are currently in the process of extending these results to fractionally-wet media.

### 3.1.2 Gas Permeability

We have developed a procedure to directly measure the gas relative permeability in water-wet and oil-wet sand packs. We pack the desired sand into a 60 cm column made out of 20 seperate 3 cm long sections of polycarbonate plastic tubing (2.54 cm diameter) which are held together with shrink tubing. The shrink tubing provides an air tight seal, and every other plastic section contains a small port through which we measure the pressure of the gas phase at various positions along the sand pack during gas displacements. We first measure the single phase gas permeability by flowing known rates of $CO_2$ through the column and measuring the pressure drops across each section using a manometer. We then fill the column with de-gassed water from below and circulate it until all of the original $C0_2$ is displaced or dissolved. Gas is then injected at a known rate at the top of the column,

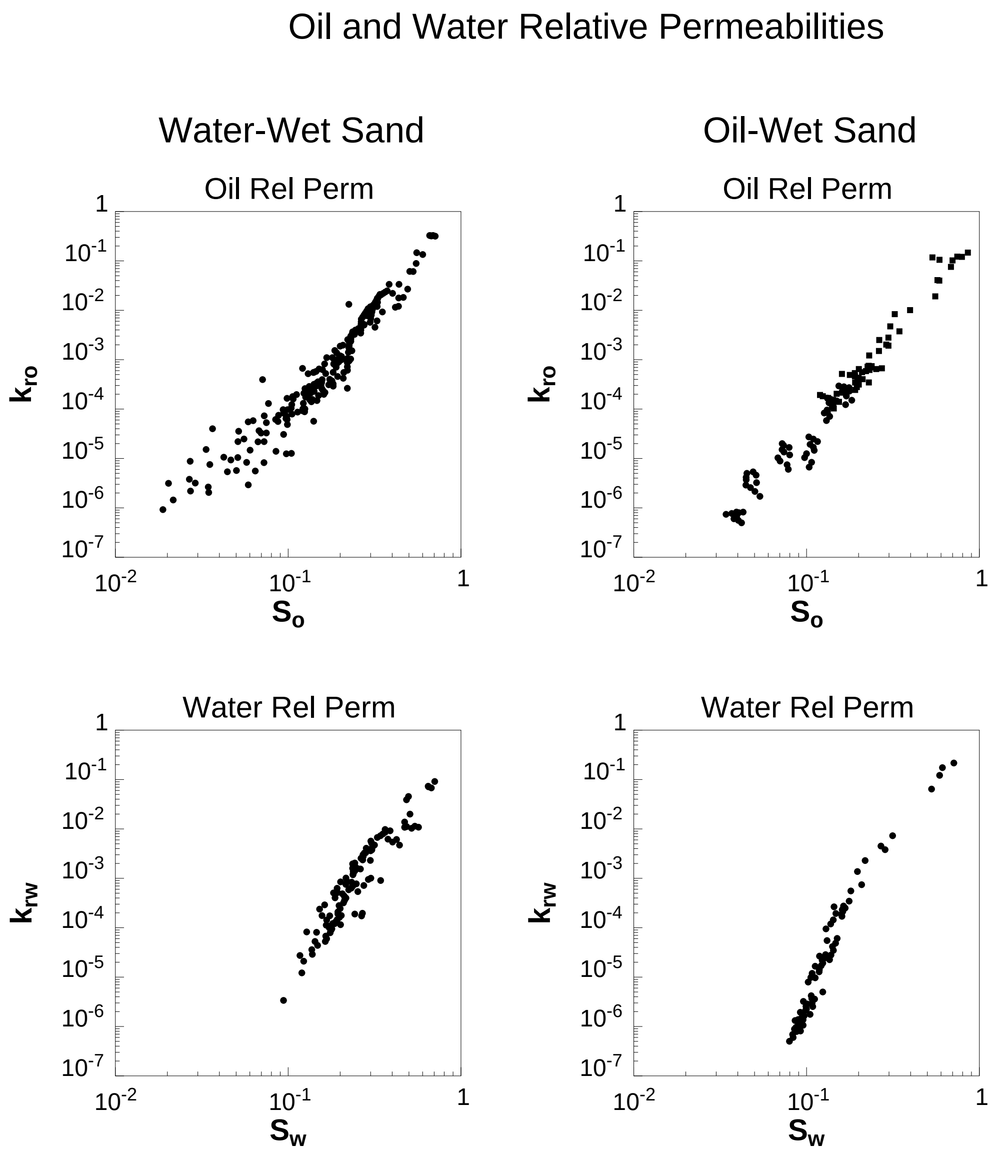


Figure 1: Measured oil and water relative permeabilities for water-wet and oil-wet sand during three-phase gravity drainage. The oil relative permeability in water-wet sand (top left) remains finite at low saturations due to the formation of oil layers.

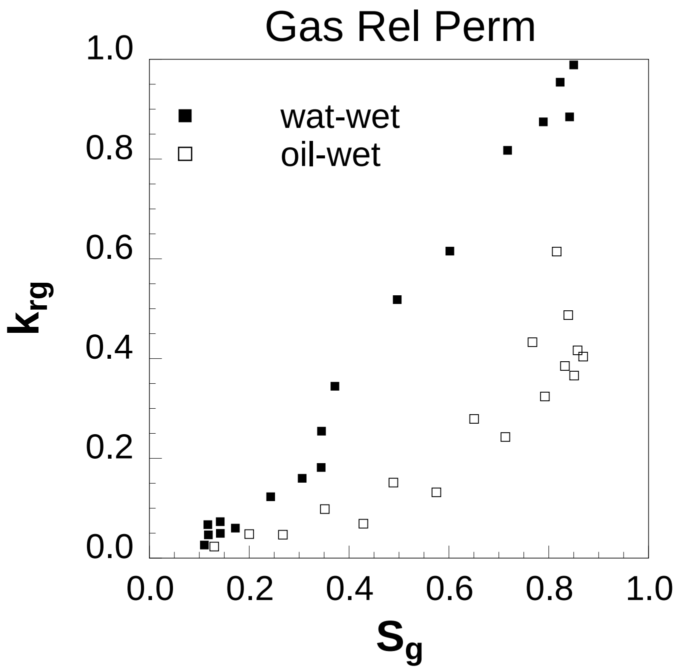


Figure 2: Measured gas relative permeabilities for water-wet and oil-wet sand during gravity drainage. The gas relative permeability in oil-wet sand is roughly a factor of two smaller than that for identical water-wet sand.

displacing the water out the bottom. This injection is continued for several hours until the pressures have stabilized and the gas and water phases are in equilibrium. Due to capillary effects, the distribution of water varies along the sand pack, and we measure the associated changes in the gas pressure drops. The pressure drops give us the gas relative permeability of each section, and we obtain the saturations by then sectioning the column and measuring the water and gas saturations gravimetrically. Using this procedure we obtain 8 measurements of the gas relative permeability for each column.

We performed these measurements on water-wet and oil-wet sands which are identical to those used in the measurements of the oil and water permeability. Figure 2 shows the measured gas relative permeabilities for both sands. We find that for intermediate gas saturations the gas relative permeability for oil-wet sands is roughly a factor of two smaller than that for identical water-wet sand.

This can be understood qualitatively as in an oil-wet medium the water and gas phases are competing for the largest pores, while in a water-wet medium the gas occupies the largest pores and channels and the water and oil phases remain in the smallest. Thus at equivalent gas saturations, in the oil-wet system the gas is in smaller pathways leading to a lower permeability.

We are currently in the process of measuring the changes in gas permeability for fractionally-wet sand packs. We are also working on a quantitative description on how the permeabilities vary with the wettability of the medium.

The work on CT measurements of three-phase relative permeability has been presented at the Tulsa EOR meeting in April 1998 [Sahni et al., 1998] . Experimental work on scaling of miscible floods, funded by this grant, was also presented at this meeting [Peters et al., 1998] . The work on pore scale modeling of three-phase flow, which has aided in the interpretation of these experiments has been published in SPE Journal [Fenwick and Blunt, 1998a] and Advances in Water Resources [Fenwick and Blunt, 1998b] .

## 3.2 Streamline-Based Simulation

The research originally planned under this section of the proposal is now complete, and further work is exploring extensions of these ideas to make streamline simulation an even more powerful tool for reservoir performance.

The streamline method has been extended to include compositional displacements. Simulations of three and four component displacements, including condensing, vaporizing and condensing/vaporizing gas drives have been performed. In all cases we have exhaustively compared the results of the streamline simulator against conventional simulation – the streamline method suffers from less numerical dispersion and is of order 100 times faster than finite difference codes for large three-dimensional simulations. We have shown that as the number of grid blocks, $n$ increases, the computer time increases almost linearly as $n$. This the optimal efficiency of any simulation method. In contrast, for a commercial simulator, the computer time scaled as $n^{3.4}$, resulting in very inefficient simulations of large models.

On the conclusion of this work, further enhancements of the streamline method are being considered. So far, the model only accommodates Cartesian grid blocks. We are presently studying the extension of the streamline tracing algorithms to grid blocks of arbitrary shape.

Streamline simulation is still limited by the time and memory requirements for computing the pressure field on a fine scale. A novel method using nested gridding is being pursued that avoids full computation of the pressure field on the fine grid, thus saving considerable amounts of computer time, without significant loss of accuracy.

The work on compositional streamlines was performed by Ph.D. student Rod Batycky, who graduated in February 1997, and by Prof. Marco Thiele. MS student Mathieu Prevost is studying streamline tracing through irregular grid blocks, and post-doc Yann Gautier is investigating the nested grid approach. Several publications on the streamline work have been published in the last year, including a description of the streamline method in the November 1997 issue of *SPE Reservoir Engineering* [Batycky et al., 1997] . The work on streamlines to model compositional displacements was presented at the SPE Annual Meeting in San Antonio, Texas in October 1997 [Thiele et al., 1997] .

# 4 Conclusions

The conclusions of our work to date are:

1. Dual energy CT scanning is a useful tool for obtaining in-situ measurements of three-phase flow from which direct measurements of three phase relative permeabilities may be obtained, down to saturations of only 2%.

2. At low oil saturations, spreading systems show a characteristic form of the relative permeability, $k_{ro} \sim {S_o}^2$. This is consistent with a theoretical interpretation of oil layer drainage at the pore scale. For a non-spreading system, the layer drainage regime was not observed.

3. In oil-wet systems, the oil permeability behaves similarly to the water permeability in water-wet systems, while the water behavior is more complex. Also, the gas relative permeability of oil-wet systems is roughly twice as small as that for identical water-wet systems.

4. Streamline methods can be extended to study a variety of field-scale displacement processes – including waterflooding, miscible displacements and compositional displacements. The method is faster and more accurate than conventional finite difference approaches.

# 5 Publications

Selected Recent Publications by the Gas Injection Research Group


Batycky, R. P., M. J. Blunt, and M. R. Thiele, A 3D Field Scale Streamline Simulator, *SPE Reservoir Engineering*, 12(November), 246-254, 1997.

Fenwick, D. H., and M. J. Blunt, Three-Dimensional Modeling of Three Phase Imbibition and Drainage, *Advances in Water Resources*, 25(2), 121-143, 1998b.

Fenwick, D. H., and M. J. Blunt, Network Modeling of Three Phase Flow in Porous Media, *SPE Journal*, 3(March), 86-97, 1998a.

Peters, B. M., D. Zhou, and M. J. Blunt, Experimental Investigation of Scaling Factors that Describe Miscible Floods in Layered Systems, SPE 39624, Proceedings of the *SPE/DOE Improved Oil Recovery Symposium*, Tulsa, OK, 1998.

Sahni, A., J. Burger, and M. J. Blunt, Measurement of Three-Phase Relative Permeability during Gravity Drainage Using CT Scanning, SPE 39655, Proceedings of the *SPE/DOE Improved Oil Recovery Symposium*, Tulsa, OK, 1998.

Thiele, M. R., R. P. Batycky, and M. J. Blunt, A Streamline-Based 3D FieldScale Compositional Reservoir Simulator, SPE 38889, Proceedings of the *SPE Annual Meeting*, San Antonio, Texas, 1997.