# MOBILISATION OF TRAPPED GAS FROM BELOW THE GAS-WATER CONTACT

A. Cable[1], D. Mogford[1], M. Wannell[2]

[1]ECL Technology Limited, Winfrith Technology Centre, Dorchester, Dorset, DT2 8DH, UK
[2]Burlington Resources (Irish Sea) Limited, 1 Canada Square, Canary Wharf, London, E14 5AA, UK

*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
Invasion by water above the original gas/water contact leaves potentially recoverable reserves in the form of a trapped gas saturation ($S_{gt}$) below the new gas/water contact. This paper describes a laboratory study to evaluate the mobilisation of trapped gas and presents the results of experiments which were performed at reservoir pressure using reservoir core material that was characterised and conditioned to provide a trapped gas saturation typical of reservoir conditions. Two depressurisation experiments were undertaken to measure critical gas saturation, gas recovery and gas-brine relative permeability. In-situ saturation monitoring (ISSM) was performed throughout.

Laboratory water flooding successfully produced uniform trapped gas saturations of 0.47 PV and 0.41 PV, values typically observed in the Field. Both depressurisation experiments saw gas mobilisation and production. The first depressurisation experiment underwent pressure decline from 117 barg to 34 barg and 70% of the initial trapped gas was recovered. For both experiments critical gas saturation was just 0.03 PV higher than the trapped gas saturation, an expansion of just 6%-7%. Measured gas and brine phase relative permeabilities were extremely low; around 0.01 at the saturation where $k_{rg}/k_{rw}=1$. Measured relative permeability curves have been modelled using core flood simulation. The final result of the laboratory experiments and their analysis is a set of relative permeability curves that could be incorporated into a reservoir model and used to simulate blow down.

## INTRODUCTION
A number of gas fields in the East Irish Sea were discovered with a residual gas leg underlying the conventional reservoir. This was caused by a rise in the gas water contact over geological time, a reservoir imbibition process. This trapped gas can reach saturations of up to 50% and could represent a significant incremental resource. However no gas has been observed to flow when tested in the field. This is probably due to the low relative permeabilities to both gas and water. This paper describes a laboratory study to evaluate the mobilisation of trapped gas and led to the derivation of a set of relative permeability curves that will be used in future reservoir simulation studies.

## EXPERIMENTAL SET UP AND PROCEDURES

Rig Description

The facility used for this study was an ambient temperature facility equipped with in-situ saturation monitoring (ISSM). The test was conducted at the reservoir pressure of 117 barg (1,700 psig). The study, although undertaken at reservoir pressure, was conducted at a laboratory temperature of 22°C. Application of reservoir temperature was not considered to be essential since wettability for the gas-water system under investigation is unlikely to be an issue (the gas phase always being the non-wetting phase). The rig could accommodate core samples of up to one metre in length although for this study a four plug composite of 32 cm in length was used. Two high pressure positive displacement pumps were used (one injecting fluids and one extracting fluids) in order to flood through the core at the required displacement rate. Typically a reservoir advance rate of around 0.5 ft/day was used; which corresponded to a laboratory flow rate of around 1.5 mL/h. In addition, a high pressure PVT cell was used as a separator to observe gas production from the core. The facility was equipped with numerous absolute pressure transducers, differential pressure transducers and thermocouples connected to a data logging system. A schematic of the facility is illustrated in Figure 1.

Core Selection And Characterisation

In consultation with the Client, core material was selected in the range of 3 mD from below the reservoir gas water contact. It was desired by the Client to study the potential for trapped gas recovery on actual reservoir core material representative of the target flow zone. Several candidate whole core samples were X-ray CT screened, plugged and brine permeabilities were measured before a suitable sample was found. Four plugs were cut from a single whole core sample along the observed bedding plane. Petrographic, SEM and mercury injection analysis undertaken showed the presence of authigenic clays (including filamentous illite) which could locally reduce permeability characteristics by bridging and blocking pore throats. Particular attention was given to brine chemistry since clay swelling from the use of low salinity brine could have caused severe and permanent permeability reduction. Following sensitivity testing, brines of 15% ($^{w}/_{w}$) were used for core flooding and a 10% solution used as a buffer during solvent cleaning. No permeability damage resulting from clay swelling was observed using these brines. It was not possible to use formation brine at the laboratory test conditions as the salinity was too high (>30%) and uncontrolled precipitation of salts would occur.

Composite Assembly And Acquisition Of $S_{wi}$

A 32.0 cm long composite core was assembled using four cut plugs. Each was trimmed and their ends squared-off in order to get good butting. The plugs were ordered such that the highest permeability plug was positioned at the outlet with remaining plugs descending in permeability towards the inlet to minimise the brine phase capillary pressure end effects. The composite was placed in a low attenuating aluminium core holder in a vertical orientation with the composite inlet positioned at the bottom (for gravity stable gas production from the top of the assembly). Following construction, the composite was brine flooded with an applied back pressure to measure the absolute permeability and acquire 100% brine saturation ISSM calibration. The brine was flushed from the composite with solvents in order to acquire the 100% gas saturation ISSM calibration, but without drying the composite which could potentially cause clay damage. Gas phase $\gamma$-ray calibration scans were obtained as a function of pressure. The $\gamma$-count rate for the gas saturated core decreased linearly with increasing pressure (increasing density) over the pressure range of the test. A sensitivity analysis showed that using a low pressure gas phase calibration at the highest test pressure of 117 barg, would potentially result in a maximum gas phase saturation error of up to 0.10 PV (depending upon actual gas phase saturation). Following the ISSM calibrations, the composite was restored to 100% brine and both the pore volume and brine permeability was measured. NaI dopant was not used in the brine phase to increase the saturation accuracy since dopant was found to cause permeability decline. The core was desaturated to $S_{wi}$ by means of gas injection at a constant inlet pressure of 30 psig and using a water-wet porous plate at the core outlet face. ISSM was used to monitor the desaturation process and the flood was terminated when a representative Field value was reached (around 30% from well logs above the transition zone). A representative value of $S_{wi}$ was desired initially in order to achieve a representative Field trapped gas saturation, since the trapped gas saturation is usually found to increase as a function of initial gas saturation (Land Correlation). The effective gas permeability at $S_{wi}$ was then measured.

<u>Water Flood To Trapped Gas Saturation</u>

The test fluids and composite core were equilibrated with nitrogen and brine at the initial test pressure of 117 barg to minimise the potential for gas dissolution i.e. to achieve an immiscible water displacement. The equilibrated brine was injected into the core at a rate of 1.5mL/h, which was equivalent to a typical field advance rate of ~0.5 ft/day. Produced fluids were measured and ISSM was used to monitor saturation changes. Post break-through, the effective brine permeability at trapped gas saturation ($S_{gt}$) was measured.

<u>Depressurisation Experiment & Steady State Gas Water Relative Permeability</u>

Depressurisation from the trapped gas saturation commenced by isolating the brine injection pump, and allowing a constant rate extraction from the outlet separator using a second pump. The separator was set up to observe gas production from the core. Definitive core saturations were measured directly from ISSM. Absolute pressures were measured at the core inlet and core outlet, together with direct measurement of differential pressure using a diaphragm type instrument. For the first experiment the composite was allowed to depressurise from 117 barg to 34 barg over a period of 24 days at a constant extraction rate of 0.34 mL/h. The effective gas permeability was determined from the measured gas production rate and differential pressure ($\Delta P$). For the second experiment the composite was depressurised at a constant extraction rate of 0.52 mL/h until critical gas saturation was observed. Steady state gas-water permeability was then measured. Four fractional flow tests using nitrogen and equilibrated brine were undertaken. The total flow rate was kept as low as practicable to minimise viscous forces, since capillary forces are dominant for the depressurisation process. Very low fractional flow was desirable, but found to be impractical. At each steady-state condition; the fractional flow, total flow rate, measured differential pressure and in-situ gas saturation was used to calculate relative permeability.

## RESULTS & DISCUSSION

The selected plugs were solvent cleaned and 100% brine saturation established. The absolute brine permeability was measured with an applied back pressure. Interestingly, the permeabilities measured were very similar to the 'as received' measurement which was a good indication that the samples chosen were initially clean (i.e. from below the gas-water contact). The received plugs were either brine saturated or at a residual gas saturation (which would have been removed by the degassing process prior to permeability measurement). The data also confirmed absence of core damage from using mild cleaning solvents and the reduced salinity brine. The core plug properties are summarised below:-

TABLE 1: Individual Core Plug Geometery and Permeability

| Plug | Length (cm) | Dia (cm) | $k_w$ (as received) (mD) | $K_w$ (abs) (mD) |
|---|---|---|---|---|
| 1 | 5.59 | 3.741 | 1.70 | 1.71 |
| 2 | 9.06 | 3.699 | 3.92 | 3.84 |
| 3 | 9.06 | 3.698 | 3.71 | 3.68 |
| 4 | 8.70 | 3.711 | 3.07 | 2.95 |
| Composite | 32.41 | 3.712 | - | 3.20 |

The composite absolute brine permeability was measured to be 3.2 mD before the depressurisation experiments and repeated at the end of the study and found to be 3.3 mD. The measured pore volume (using ISSM techniques) of 70.6 mL corresponded to an average porosity of 20.4%.

The composite was desaturated in 66 days with a final $S_{wi}$ of 0.29PV. The brine distribution at $S_{wi}$ may be seen in Figure 2. The observed brine distribution was heterogeneous and probably attributed to core character, although it is noted that without NaI dopant in the brine phase, optimum saturation accuracy has not been achieved for this study. Note also that all ISSM profiles presented in this paper have been selected from a vast amount of data and noise at the plug butts has been removed in order to simplify presentation. The effective gas permeability measured at $S_{wi}$ (at 117 barg) was 6.64 mD, approximately twice the measured absolute brine permeability. Klinkenberg correction was not required as the effective gas permeability was measured at high absolute pressure and therefore should be close to the 'theoretical liquid' permeability (and directly comparable with the absolute brine permeability measurement).

<u>Water Flood to Trapped Gas Saturation</u>

The gas saturated core at $S_{wi}$ was water flooded at a typical field advance rate of ~0.5 ft/day (1.5 mL/h in the laboratory) and resulted in a trapped gas saturation of 0.47 PV.

Figure 2 shows the measured in-situ trapped gas saturation at 117 barg with three flood fronts shown progressing towards the top of the core ($S_w$ scans 1, 2 & 3). The brine saturation is shown increasing from an average of 0.29 PV (at $S_{wi}$) to 0.53 PV at the flood cessation. As expected, no post break-through production of the non-wetting gas phase was observed. The brine flow rate was reduced to 0.34 mL/h from which the brine permeability was calculated to be 0.22 mD. This corresponded to a relative permeability $k_{rw}$ of 0.033 (using the measured 6.64 mD $k_{eg}$ at $S_{wi}$ as the reference permeability). This brine permeability is very low, but not unexpected, since the high trapped gas saturation will occupy all of the largest pore sizes (being non wetting) effectively blocking the brine phase mobility. Figure 3 compares the trapped gas saturation of 0.41 PV acquired before the second depressurisation experiment with the first. This saturation was established by repressurisation (following the first depressurisation experiment) and again water flooding at 1.5 mL/h. This method, which resulted in a slightly lower trapped gas saturation, avoided the need to re-establish $S_{wi}$ by primary drainage before water flooding (which would have been very time consuming). A slightly higher brine relative permeability of 0.036 was measured at this lower trapped gas saturation.

Depressurisation Experiments & Steady State Gas Water Relative Permeability

Composite depressurisation commenced by isolating the brine injection pump immediately following brine permeability measurement and continuing with constant rate extraction. Depressurisation from 117 barg to 34 barg took 24 days. Figure 4 shows the system pressure decline with elapsed time for both experiments. The observed gas production and measured in-situ gas saturation profiles for Experiment 1 are shown in Figures 5 and 6. Only a very small gas saturation change of 0.04 PV was measured from the trapped gas saturation to the maximum gas saturation. Figure 7 presents the average in-situ brine saturation with pressure decline. Similarly, only a saturation change of 0.05 PV was observed for Experiment 2. The measured gas production rate of 0.25 mL/h observed in the gas separator (Figure 5) is made up of three components: (1) produced gas from the expansion of trapped gas in the core; (2) the gas expansion of the initial gas present in the separator; (3) and the produced gas from expansion of evolved gases from the live brine (which was calculated to be negligible). Initial gas production was produced at a rate of 0.10 mL/h which corresponded to the expansion rate of the 24.3 mL of gas initially in the separator. The expansion rate of the gas in the composite is therefore 0.15 mL/h. This observed volumetric gas rate was consistent with the calculated gas rate of 0.15 mL/h derived from in-situ saturation data. Downstream of the separator, a 1 Litre accumulator also contained dead volume gas which contributed to an expansion rate of around 0.08 mL/h. The observed gas production rate of 0.25 mL/h and the dead volume gas expansion rate of 0.08 mL/h was in agreement with the pump extraction rate which was set to 0.34 mL/h. It is difficult to see the very small saturation changes in Figure 6, however it does show that the brine saturation decreases uniformly along the whole composite length. Only a few of the distribution profiles are shown and all those from below 90 barg have been omitted for clarity. From around 90 barg to 34 barg, the in-situ saturation show unexpected, but small increases in brine saturation. This is believed to be a scanning inaccuracy and the most likely explanation is a small change in the attenuation of the core holder annulus fluid (the calibration reference scans support this). The annulus fluid was initially at 117 barg ($N_2$-oil) and the 'live' oil may have degassed and become more attenuating at the lower core pressures.

Maximum gas saturation was first apparent from ISSM measurements at around 100 barg for both experiments corresponding to an expansion of just 8.5%-12% of the in-place trapped gas. The measured differential pressure is shown for this initial 96 hour period in Figure 8. Initially only brine is produced and ultimately at the lower system pressure, it could be assumed that entirely gas is produced. At the start of the depressurisation, the $\Delta P$ falls dramatically, which is attributed to the falling displacement rate (from 0.34 mL/h following measurement of $k_{ew}$, to around 0.15 mL/h; the trapped gas expansion rate). Once the rate stabilised, the $\Delta P$ slowly increased, as would be expected, since the expanding gas (before critical gas saturation) impedes brine phase mobility. From Figure 8 the $\Delta P$ is seen to peak at around 105 barg (Experiment 1) before declining which might be an indicator for flowing gas. At 105 barg, the in-situ gas saturation was measured to be about 0.50 PV so we could estimate $S_{gc}$ to be about 0.50 PV (or just below). Note that the gas is not observed in the separator for another 3 days due to the outlet dead volume of 10 mL. Ultimately (for Experiment 1) the pressure drop is seen to be around 3.8 psi (for the last 6 days) which at 0.15 mL/h corresponds to a gas relative permeability of around 0.001. For Experiment 2 there was a noticeable change in $\Delta P$ characteristic between 106 barg to 107 barg corresponding to an in-situ gas saturation of 0.44 PV. So again we could estimate $S_{gc}$ to be about 0.44 PV which compares to the measured maximum gas saturation of 0.46 PV. For both experiments $S_{gc}$ was just 0.03 PV higher than the trapped gas saturation, which is an expansion of 6%-7%.

Steady state was achieved at $fw$=2.5% in 9 days. Very little pressure or gas saturation change was detectable. However, the injected brine flow rate of 0.013 mL/h was measured in the outlet separator. Steady state was also achieved in 9 days at $fw$=5.0%. For the third and fourth fractional flows, the total rate was increased from 0.52 mL/h to 1.5 mL/h. Steady state was achieved in 5 days at $fw$=10.0% and 2 days at $fw$=100.0%. The results are summarised in Table 2. The fractional flow data and measured end-point relative permeabilities are plotted in Figure 9. Measured secondary drainage capillary pressure is given in Figure 10, which was used for core flood simulation.

TABLE 2: Steady State Gas-Water Relative Permeability

| Fractional Flow $f_w$ | Gas Flow (mL/h) | Brine Flow (mL/h) | $\Delta P$ (psi) | $k_{rg}$ | $k_{rw}$ | $S_g$ (PV) | Secondary Drainage $P_c$ (psi) |
|---|---|---|---|---|---|---|---|
| 2.5% | 0.507 | 0.013 | 6.07 | 0.0030 | 0.0045 | 0.465 | 0.64 |
| 5.0% | 0.494 | 0.026 | 7.39 | 0.0024 | 0.0074 | 0.450 | 0.22 |
| 10% | 1.350 | 0.150 | 22.62 | 0.0022 | 0.0139 | 0.445 | 0.08 |
| 100% | 0.000 | 1.500 | 116.7 | 0.0000 | 0.0269 | 0.426 | 0.00 |

## CONCLUSIONS

Two depressurisation experiments have been successfully undertaken from uniform trapped gas saturations of 0.47 PV and 0.41 PV, values typically observed in the subject Field. Both depressurisation experiments saw gas mobilisation and production. Critical gas saturation was just 0.03 PV higher than the trapped gas saturation, which is an expansion of just 6%-7%. The first depressurisation experiment underwent pressure decline from 117 barg to 34 barg and 70% of the initial trapped gas was recovered. Measured relative permeability curves have been estimated from low rate steady state flooding. Gas and brine phase relative permeabilities were extremely low; around 0.01 at the saturation where $k_{rg}/k_{rw}$=1. It is reported in the literature that solution gas ‘internal drive’ relative permeability might be an order of magnitude lower than relative permeability derived from conventional, unsteady state and steady state measurements [1, 2, 3, & 4]. The analysis techniques we have used to derive internal drive relative permeability from measured in-situ saturation and pressure data from the current study (and studies on 20 mD and 0.01 mD core) are expected to be published at a later date.

For this report, we have used $k_{eg}$ at $S_{wi}$ (6.64 mD) as the reference permeability to define the relative permeability curves $k_{rg}$ and $k_{rw}$. Particular attention has been given to experimental methods because of the unusual character of the material. It is noted that care should be taken when interpreting routine SCAL data on similar material, given that the plug history (e.g. drying, solvent cleaning) and saturation state (gas, oil or brine) may significantly alter core characteristics. The presence of filamentous illite has been identified and it is possible that the clay collapses when dehydrated in the presence of 100% gas phase (potentially opening up pore throats, otherwise bridged when the clay is swollen in the presence of brine). The effective gas permeability at $S_{wi}$ was higher than the absolute gas permeability which may be a result of a ‘lubrication effect’. Additional (independent) laboratory analysis undertaken on this core also reported similar permeability ‘anomalies’. Published papers describing similar effects have also been identified for reference [5, 6, 7].

## ACKNOWLEDGEMENTS

This work was performed as part of a SCAL Study for Burlington Resources (Irish Sea) Limited whose permission to publish is gratefully acknowledged. The Authors also wish to thank David Element for his modelling and simulation of measured experimental data.

## REFERENCES

[1] "Experimental Studies on the Water Flood Residual Gas Saturation and Its Production by Blow Down" T. Fishlock, R. Smith, M. Soper & R. Wood SPE15455 (1988).

[2] "Critical Gas Saturation and Super Saturation in Low Permeability Rocks" J. Kamath & R.E. Boyer SPE26663 October 3-6 1993.

[3] "Relative Permeability Measurements for Post Water Flood Depressurisation of the Miller Field North Sea" P. Naylor, T. Fishlock. D. Mogford & R. Smith SPE 63148 October 1-4 2000.

[4] "Depressurisation Under Tertiary Conditions In The Near Well Bore Region: Experiments, Visualization And Radial Flow Simulations" P. Egermann, S. Banini & O. Vizika SCA2003-15 September 21-24 2003.

[5 ] "Abnormal Permeability Behaviour of a North Sea Sandstone Reservoir" M.Mikklesen & A.Scheie SPE 22600 October 6-9 1991.

[6] "Effect of Strong Wetting on End-point Relative Permeability" by Colin McPhee, Edinburgh Petroleum Services Ltd. Dialog July 1994.

[7] "Relative Permeability Measurements: An Inter-Laboratory Comparison" C.A.McPhee & K.G.Arthur SPE 28826 October 25-27 1994.

# FIGURES

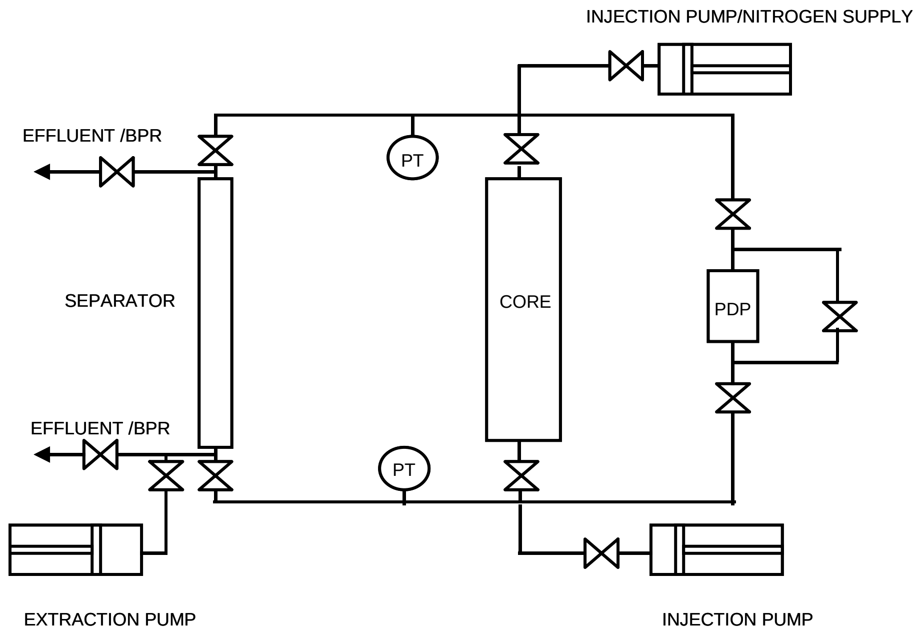


FIGURE 1: Schematic of the Depressurisation Rig

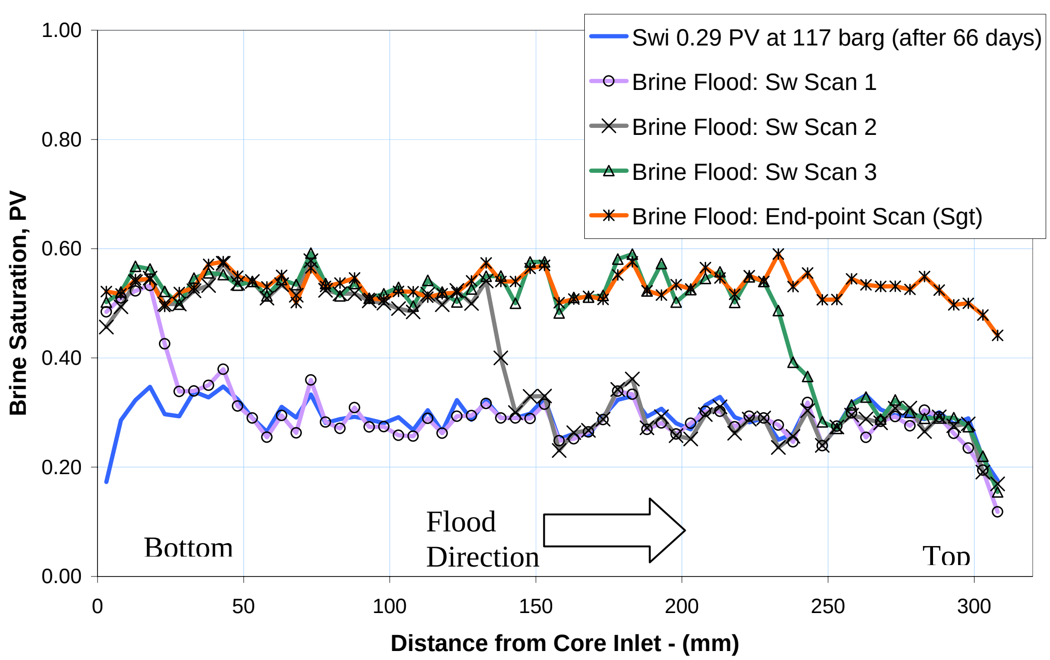


FIGURE 2: Brine Flood to Trapped Gas Saturation

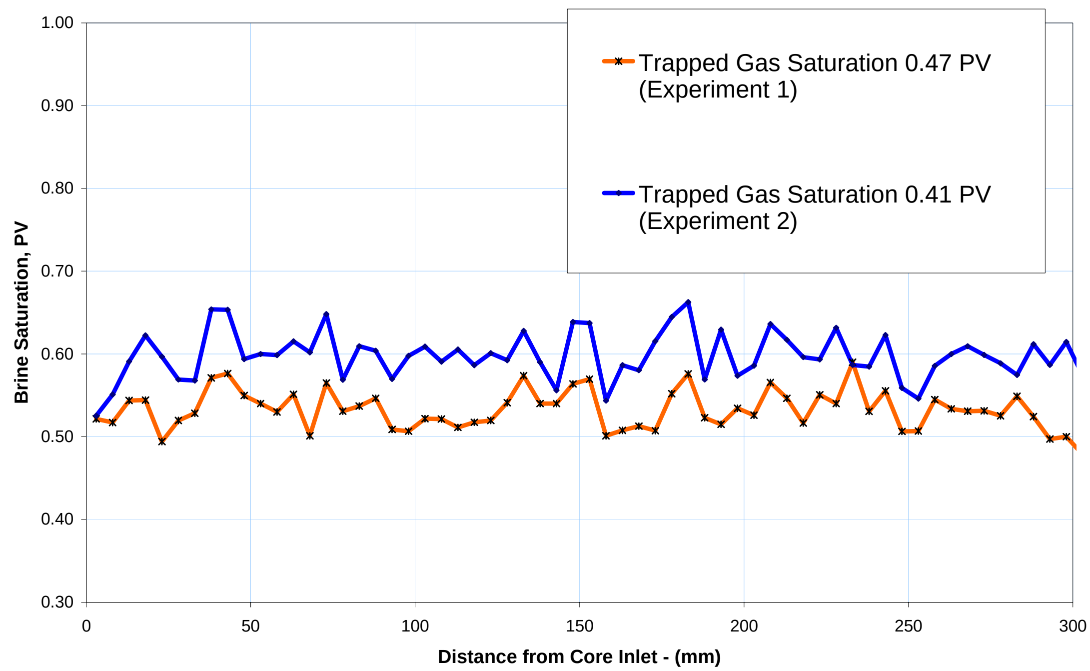


FIGURE 3: Measured Trapped Gas Saturation and Distribution

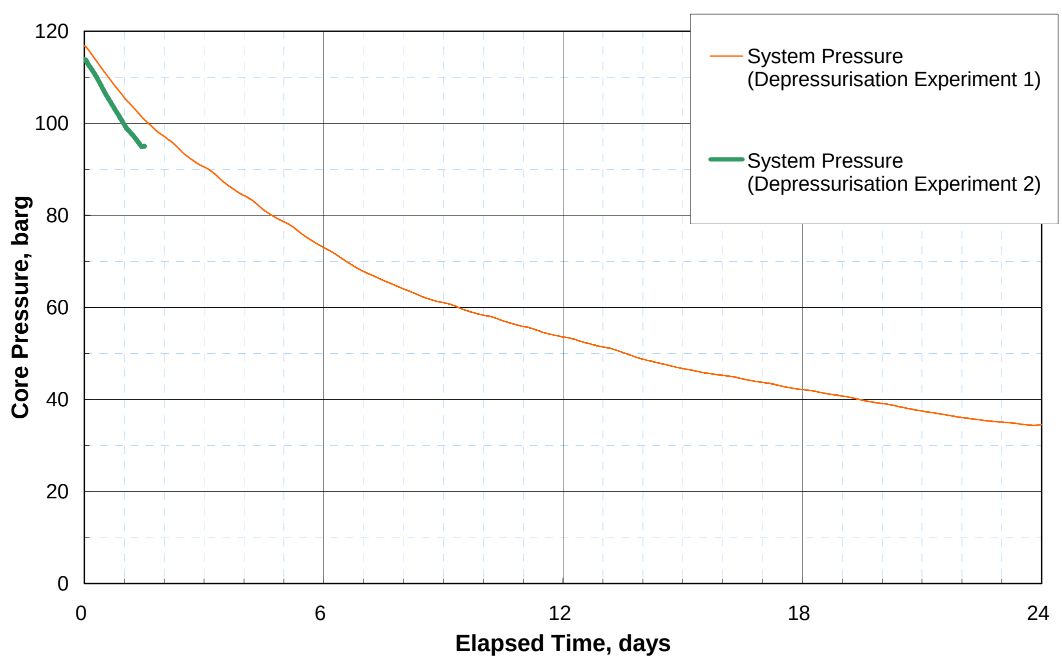


FIGURE 4: System Pressure Versus Elapsed Time

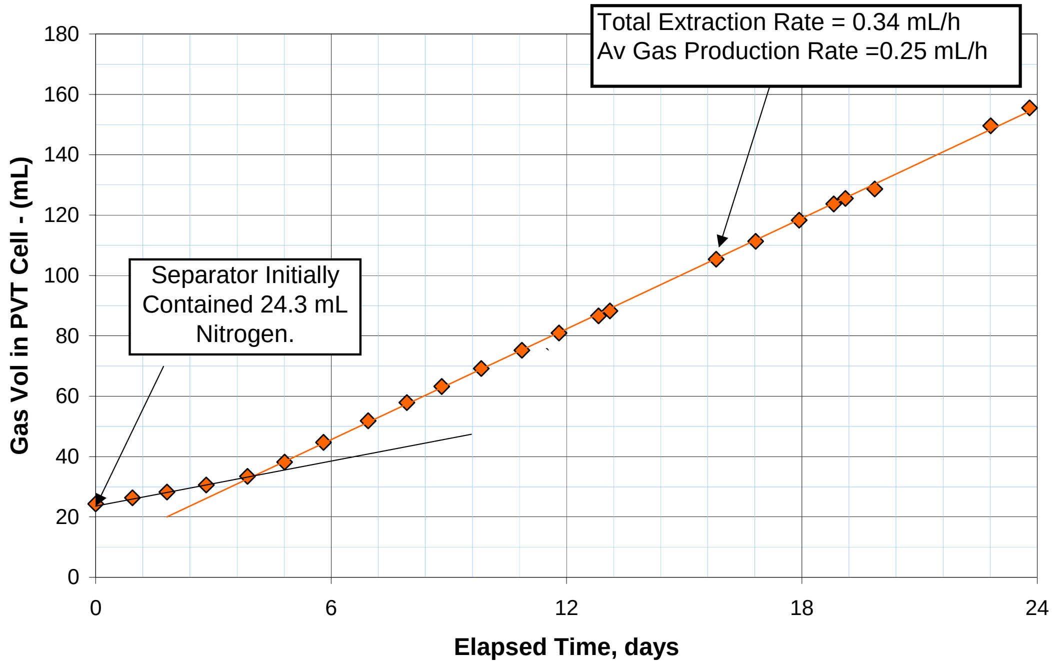


FIGURE 5: Observed Cumulative Gas Versus Elapsed Time (Experiment 1)

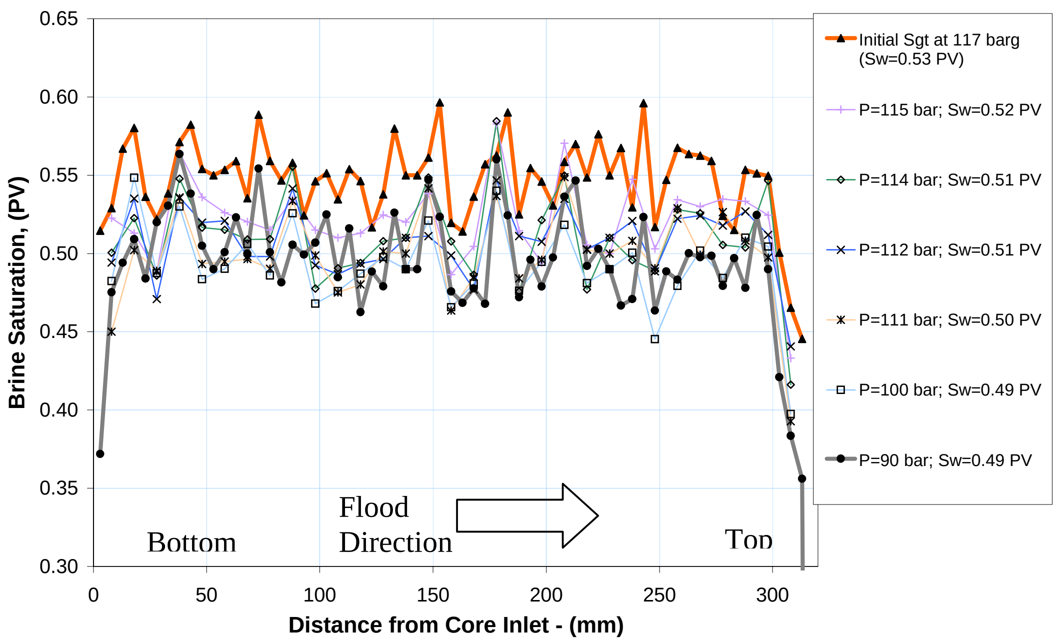


FIGURE 6: Measured In-situ Brine Saturation (Experiment 1)

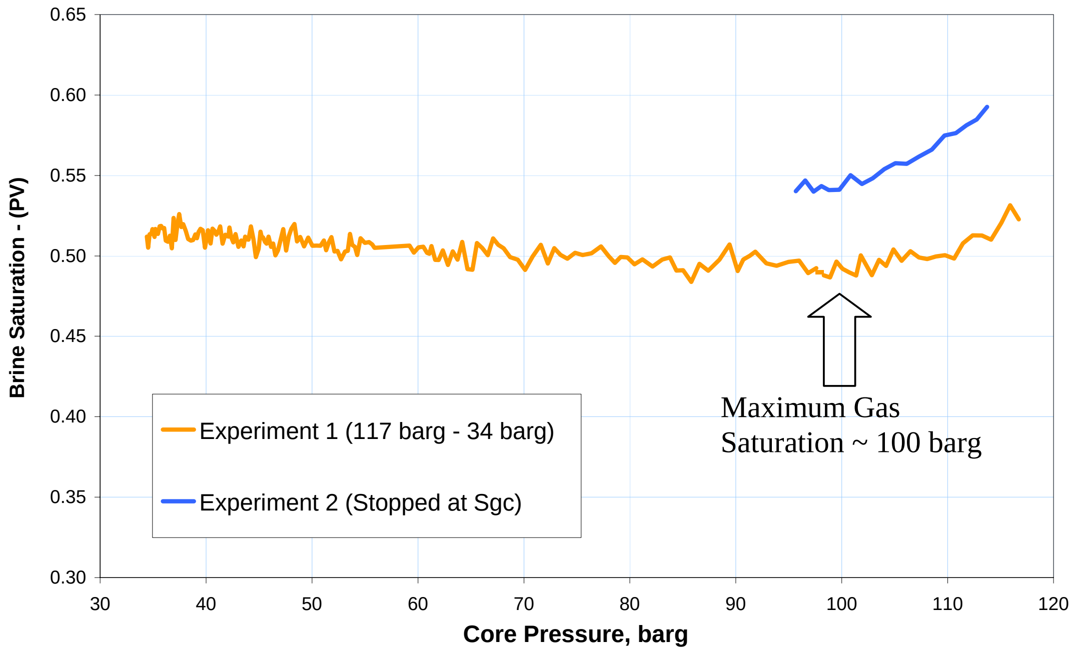


FIGURE 7: Average In-situ Brine Saturation Versus Pressure

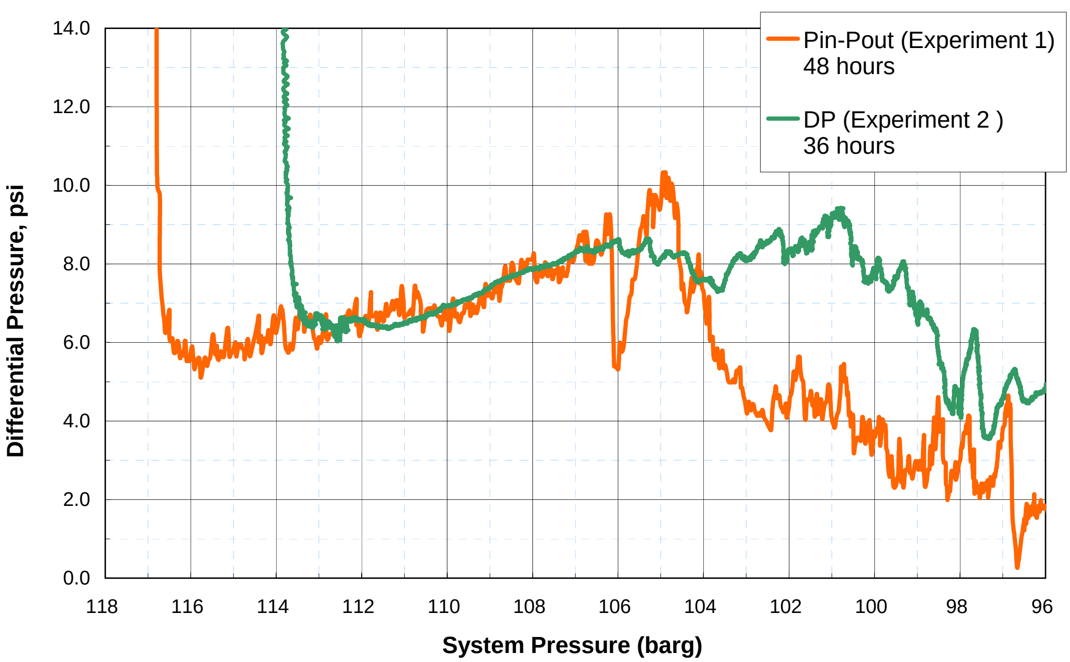


FIGURE 8: Measured ΔP Versus System Pressure (Elapsed Time 48 hours)

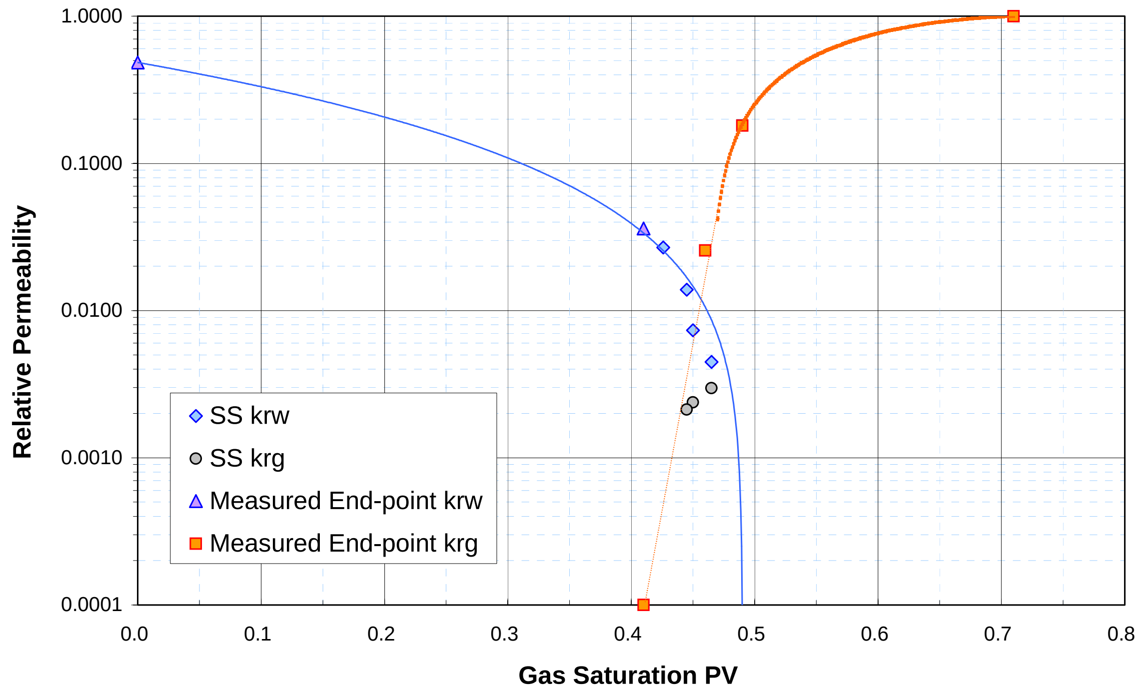


FIGURE 9: Steady State Gas-Water Relative Permeability (at 95 barg)

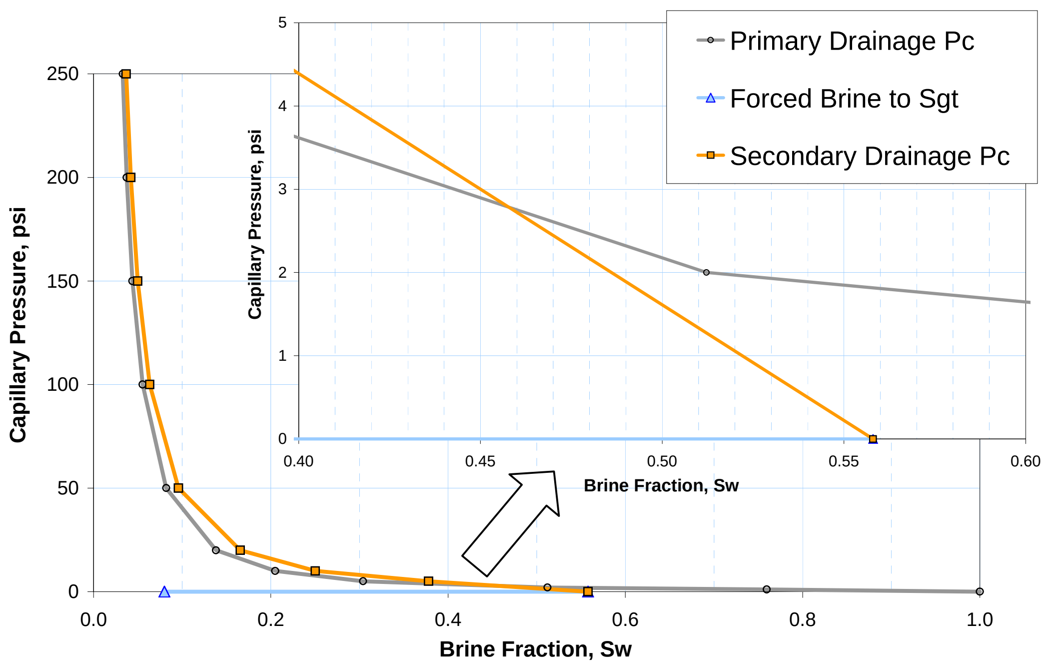


FIGURE 10: Secondary Drainage Capillary Pressure Measurement