

IOR-07 PULSE INJECTION TECHNOLOGY FOR IOR

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Abstract

This study investigated the effects of pressure pulsing on laboratory SCAL measurements using an unconsolidated and consolidated sand, refined oils and γ -ray in-situ saturation monitoring (ISSM). Published literature presented at the 1999 European IOR Symposium has suggested that under pulsed flow conditions, Darcy's law may no longer be a valid description of single phase flow and that suppression of viscous fingering may also lead to significant improvement in oil productivity.

It was possible to reproduce the published single phase data, but our measurements showed that by careful measurement of the flow rate and pressure transients, the "enhanced" flow observed was an experimental artefact, both in the case of unconsolidated and consolidated core. Our measured differential pressures and flow rates, whether using pulsed flow or unpulsed flow, always obeyed a linear extrapolation as expected for Darcy flow.

Results from two phase measurements however, did show an effect when pulsing the injection fluid (brine in this case). When water flooding the oil saturated sand, the pulsed waterflood was found to exhibit an increased brine phase mobility. It may be possible that the pulsing energy is sufficient on a pore level to overcome localised capillary pressure effects. A capillary pressure of +0.3 psi was measured for the unpulsed water floods at the point of water breakthrough, indicating water wet behaviour for these saturations. This capillary pressure at breakthrough was not observed for the pulsed waterflood (which would normally be indicative of a more oil wetting character). We observed earlier breakthrough and an increase in k_{rw} for the pulsed waterflood. The increase in brine relative permeability is an undesirable feature, and correspondingly the measured oil production was lower for the pulsed data. The ISSM data showed no evidence of suppression of viscous fingering and improved flood front stability.

In this study there were no obvious benefits from pulsing in either single phase or two-phase flow. In the field, there may be other benefits not related to the laboratory scale tests, such as the pressure wave causing changes to the near well reservoir architecture, or unblocking bridged perforations in high permeability sands.

INTRODUCTION

High amplitude, low frequency pressure pulsing was developed as a new workover technique and has been used in heavy oil wells in Alberta and Saskatchewan since October 1998. Work presented at the 1999 European IOR Symposium suggested that under pulsed flow conditions Darcy's law may no longer be a valid description of fluid flow in porous media [1-3]. In laboratory studies (with conditions representative of Canadian unconsolidated viscous oil fields) significant flow enhancement in single phase tests and suppression of viscous fingering in two-phase displacements were observed [4, 5]. This work is some of the first direct laboratory evidence supporting "vibrational methods" as a possible IOR technique.

The study was commissioned by the UK Department of Trade and Industry's Sustainable Hydrocarbons Additional Recovery Programme (SHARP), which assesses the potential of new and innovative IOR techniques that may be relevant to UKCS fields. The study we present in this paper set out to reproduce published results and to quantify whether Darcy's law is valid for one and two phase flow under conditions of pulsed injection.

REPORTED LITERATURE

Flow enhancements as high as 82% have been reported under pulsed flow conditions [4]. The experimental set up consists of a sandpack to which fluid is delivered from a constant head device and the produced fluid volume measured as a function of time. Pulsed flow was achieved with a manual squeeze or the impact with a rubber mallet on the TygonTM inlet tube, although in more recent studies by other workers a Consistent Pressure Source (CPS) is being used which repeatedly pressurises and depressurises a water inlet vessel with compressed air [6].

A key issue associated with the interpretation of the reported results is whether the pulsing action contributes a component of pumping to the system. In principle, the act of compressing the inlet pipe locally with a mallet could force a wave of fluid into the core and/or back into the constant head device where it would not be noticed. For typical reported results this would only need to be of the order of 0.001 to 0.01 mL per pulse. When the pipe relaxes (over a slower timescale determined solely by its physical character) fluid is drawn from the constant head device, in preference to the core, because of its lower flow resistance. Manual pulsing may also provide the opportunity to force additional fluid through the core if the pipe is progressively squeezed towards the core inlet using a "milking" action.

Davidson et al also report that viscous instabilities can be controlled through pressure pulsing [5]. The authors presented their observations from waterflooding a sandpack slab of approximately 35% porosity:

- (1) saturated with 1600 cp heavy oil at a connate water saturation of 10%,
- (2) 100% saturated with paraffin oil of 35 cp.

It was this second test that we aimed to investigate. For the first test, the unpulsed flood duration was around 45 minutes during which time a total production of 200 mL was measured, ~4 mL/min, at which point the oil production was reported as 35% (taken to mean 70 mL of oil from the 200mL of total produced fluids). A repeated test with pulsing produced around 200 mL in 38 minutes, ~5 mL/min, with an oil fractional production of 90% (taken to mean 180 mL of oil). Similar observations were noted for the second experiment, albeit at a much faster rate (6 minutes duration at around 60-100 mL/min). It is difficult to draw any conclusions from this data without oil production data, however, the suggestion is that there is a significant improvement in sweep efficiency when pressure pulsing, even if the increase in total flow rate can be explained as a laboratory artefact.

Recent theoretical studies of oscillatory flow of droplets in straight and constricted capillary tubes [7, 8] have shown significant increases in flow, for both the continuous and droplet phases. In constricted tubes there is also the possibility of oscillatory flow overcoming trapping of droplets at constrictions.

SINGLE PHASE FLOW - METHODOLOGY

Core Flood Data Analysis

If additional pumping components are present as a result of pulsing, increased flow rates may be observed. The use of the constant head device *will not* ensure that the pressure drop across the core is unchanged. It is therefore not sufficient to examine only plots of fluid production against time alone. Any increase in effective pressure drop across the core also needs to be taken into account.

The frequency of pulsing used in the reported laboratory studies is of the order of 1 Hz, which is very rapid compared to the timescales for changes in reservoir flow. Therefore, in the first instance, it is useful to test whether any special physical phenomena that could occur during pulsed flow can be understood within a framework of time averaged quantities. The validity of Darcy's Law for pulsed flow has been carefully assessed by comparing the average pressure gradient and average flowrate in vertical sand packs and consolidated cores to determine an effective permeability k_{pulse} under pulsing defined by:

$$\int q(t)dt = \frac{Ak_{pulse}}{\mu L} \int (p_{in}(t) - p_{out}(t) + \Delta\rho gL)dt$$

where the pressure differential has been corrected for a zero flow offset. Evaluation of the flowrate integral is straight forward since it corresponds to the total volume of fluid collected during the flow test. The pressure integral is more difficult to evaluate because of the rapidly varying pressures at inlet and outlet, and requires a large data sample to achieve statistically accurate results. In particular, if the sampling frequency is not significantly higher than the pulsing frequency, the issue of beat frequencies in the pressure data needs to be addressed.

Pulsed and unpulsed data for a range of heads and pulsing methods has been analysed by performing a linear regression between the average flowrate and gravity head corrected pressure differential. The slope of the lines correspond to the conventional permeability and effective permeability under pulsed conditions, k_{pulse} .

Flow Circuits

Three variations on the constant head flow circuit were considered:

- A flow circuit (Figure 1) which uncoupled flow effects from pulsing action so that both effects could be quantified independently. This was achieved by adding a second pump to a constant head flow circuit that operated as an independent closed loop, but delivering a pulse to the core inlet. The second pump could be used with a choice of pump heads, delivery rate and refill rate so that a range of pulse frequencies (and to some extent the shape of the pulse waveform) could be investigated.
- A flow circuit where the pulsing pump actually delivered the pulsed flow to the core, the idea being that the pulse is "carried" with the delivered fluid volume (Figure 2). Care was taken to record the flowrate through the core in addition to measuring the total delivered volume from the pulse pump and constant head device. If flow could not be dissipated completely via the core it would overflow from the constant head device. Two balances and a small measuring cylinder were used to measure all flows.
- A circuit (Figure 3) which allows the use of a manual, hand held pulser. This set up was used to reproduce the published pulsing technique and pressure transients [4, 5] and compare with the first two mechanical pulsing methods.

SINGLE PHASE FLOW MEASUREMENTS

A total of over 60 tests were undertaken, which explored a wide range of variables including:

- Three constant heads (rates) with pulsed flow and unpulsed flow.
- Two fluids with different viscosities (dekalin 2.5 cp and light paraffin oil 25.5 cp) with pulsed flow and unpulsed flow.
- Variable pressure pulsing frequencies (0.2 Hz, 0.4 Hz, 1.0 Hz and 2.0 Hz).
- Pulsing device without flow, with flow and manual pulsing (by hand).
- Change in rock type (100 md consolidated sandstone and 13,500 md sandpack) with/without confining stress.

Unconsolidated sand with 2.5 cp oil

Results from tests on the sandpack with a 2.5 cp oil are summarised in Figure 4, which plots the average gravity head corrected differential pressure against the measured flow rate. In the pulsed measurements there is evidence for slightly reduced flowrates compared with unpulsed measurements, however, this is associated with slight reductions in pressure differential, such that linear regression analysis of the two sets of data shows that the pulsed and unpulsed data lie on lines with the same gradient (within statistical uncertainty). Therefore, the pulsed and unpulsed measurements show the same effective permeability, provided the actual averaged pressure differential is considered, rather than the nominal head for the system, as determined by the constant head device.

Unconsolidated sand with 25 cp oil

Results from tests on the sandpack with a 25 cp oil are summarised in Figure 5. There is some evidence for increased flow under pulsed conditions, however, this is associated with increased pressure differentials. As in the case of the set of measurements with the 2.5 cp oil, the pack behaves with the same effective permeability under pulsed and unpulsed flow conditions.

Davidson et al [4] recommend a rapid rise time, a slow decay time, and that a new pulse should be generated before the old pulse completely decays. This method of pulsing is said to generate a “synergetic pressure build up”. Tests using a manual pulsing method were also investigated. The system pressure transient from one manual pulse is shown in Figure 6. The average volume displaced by one manual pulse was measured to be 0.91 mL, which is significantly higher than that achieved by the mechanical pulsing pumps used in this study. A test was conducted with a series of approximately 270 pulses over 15 minutes. This led to a very significantly enhanced flow rate of 81.4 mL/h, compared to 3.96 mL/h for the unpulsed measurement. However, the manual pulsing resulted in the inlet pressure rising to between 9 psi and 12 psi, with an average pressure drop of 10.4 psi. This additional data is shown in Figure 7, where it can be seen that it follows the extrapolated regression lines for the low rate data (both pulsed and unpulsed) perfectly. This demonstrates that Darcy Law is still valid for the average pressure drop and flowrate.

Consolidated sand with 25 cp oil

These measurements were made in consolidated sand (100 md) using the flow circuit where the pulsing pump delivered the pulsed flow to the core. Results are summarised in Figure 8. This shows that significant flow enhancements were observed, however these always correspond to increases in the average applied pressure differential. Regression analysis finds the same effective permeability for pulsed and unpulsed flow, including the manual pulse data (within statistical error). Our results also showed that the consolidated core was much more attenuating than the sandpack. The pressure pulse, which is very evident at the core inlet, decayed along the core length of 25 cm to the extent that the outlet pressure pulse was barely detectable, unlike the pulse characteristic shown in Figure 6 for the 70 cm long sandpack.

Discussion

Enhancements in flow have been observed during pulsed flow, however, in all cases these corresponded to increases in the average pressure drop applied to the core, and the effective permeability for pulsed flow was the same as that found in unpulsed flow.

TWO PHASE FLOW MEASUREMENTS

Method

Two phase flow measurements were made using the sandpack used for the single phase flow studies. The sandpack was aged for some time in stock tank oil (STO) prior to the first pulse injection study, and was known to be of intermediate/mixed wetting characteristic. The flow circuit used the pure, mechanical, pulsing method illustrated in Figure 1. γ -ray in-situ saturation monitoring was used to provide further information about any differences in flooding characteristics when using pulsed brine injection. Using

this technique involved taking calibration scans with the sandpack fully saturated with doped brine (3% NaI brine) and fully saturated with the light paraffin oil. Core scanning was undertaken throughout the study and the in-situ oil saturations calculated.

Waterfloods were conducted with the sandpack initially filled with 100% light paraffin oil to correspond to the conditions used in [5]. The water flood procedure adopted for each test was identical. An initial low flooding rate of 4 mL/h (approximate frontal advance rate of 0.5 m/day) was followed by a bump flood at 400 mL/h.

Results

For the first two waterfloods (WF1 and WF2) no pulse was applied. For both waterfloods, an instantaneous pressure transient of +0.3 psi was observed at the point of breakthrough. This is indicative of water-wet behaviour at these saturations, and there is a small delay in breakthrough as the water phase pressure builds up to overcome the outlet capillary pressure effect. This pressure transient was not observed for the pulsed waterflood (WF3), which would normally be indicative of a more oil-wetting character. Figure 9 shows the breakthrough pressure transients, which was observed earlier in the case of the pulsed waterflood.

TABLE 1: Observed Breakthrough

Flood	Brine Injected at Breakthrough, PV
WF1	0.34
WF2	0.28
WF3 (pulsed waterflood)	0.25

To agree with the observations of Davidson et al [5] later water breakthrough would have been expected if the effects of pulsing are to stabilise the flood front and suppress viscous fingering. The γ -ray in-situ saturation data close to breakthrough did not reveal any obvious differences in flood characteristics. The saturation profile pre-breakthrough is heterogeneous. Local zones that are more oil wetting than the rest of the sandpack are apparent, and initially the injected brine is unable to invade these areas until the continuous water phase (inlet pressure) overcomes capillary pressure to match the oil phase outlet pressure. At later times, after water breakthrough, the brine is observed to access more pore space and the saturation distribution is more uniform. Figure 10 shows the in-situ, residual oil saturation following the low rate flood which also shows some degree of oil retention in the last 10-15cm of the core, but much more dramatic is the local “inlet effect”. This oil retention (which is a laboratory measurement artefact) will suppress the measured core averaged brine permeability, compared to the true reservoir value.

Figure 11 shows the measured differential pressure and Figure 12 the corresponding oil production data for the three, low rate, waterfloods. The decline in differential pressure for the pulsed waterflood (WF3) is very noticeable. The oil production under pulsed flow is slower, with 0.65 PV produced after a brine throughput of 2.25 PV, compared to 0.78 PV and 0.74 PV for the unpulsed waterfloods 1 and 2 respectively. These results are consistent with an increased total mobility for the fluids, but with the water relative permeability enhanced compared to the oil relative permeability. The oil production and pressure drop data show that there is a long post breakthrough recovery of oil. This is characteristic of an oil- or intermediate-wetting core.

The data for 50 hours (approximately 1.7 pore volumes brine injected) has been replotted in Figure 13 to approximate “total produced fluids”, under conditions of constant pressure drop. This is possible by normalising the measured differential pressure data to the pressure at the beginning of the flood. Presenting the data in this way shows that it is consistent with the enhanced total flow observed and reported in [5], but not in terms of oil recovery.

At the cessation of low rate flooding, the rate was increased to 400 mL/h so that the viscous forces resulting from fluid flow would dominate over the pore scale capillary pressure forces. The measured differential pressure for each waterflood are shown in Figure 14. End point data for both the low and

high rate floods (normalised to an oil relative permeability of 1 at 100% oil saturation) are summarised in Table 2 below:

TABLE 2: Waterflood, Measured End Point Data

Flood Rate	Observed Oil Production, PV			Relative Permeability, k_{rw}		
	WF 1	WF2	WF3 (pulsed)	WF 1	WF2	WF3 (pulsed)
Low	0.78	0.75	0.80	0.091	0.100	0.306
High	0.85	0.86	0.82	0.746	0.705	0.722

The brine phase relative permeability are shown in Figure 15. The low rate JBN analysis data is only presented to give an indication of the shape of the relative permeability curves (derived from the post-breakthrough production data given in Figure 12 in conjunction with the pressure data given in Figure 11). The brine relative permeability is markedly increased for the pulsed waterflood at the low rate. The oil relative permeabilities are all similar for the pulsed and unpulsed low rate floods. However, the oil relative permeability is lower at high rate when pulsing and it is evident from Table 2 that end-point S_{or} is higher for the pulsed data, so there has been no recovery improvement.

Discussion

In contrast to the results of the single phase tests, measurable differences between unpulsed and pulsed waterfloods have been found. These are consistent with enhanced flow for pulsed flooding, but unlike the results presented in [5] show a lower recovery for a given number of PV injection, or for given time if the results are scaled to a constant pressure drop. In comparing the results it is important to recognise two differences:

- This study used lower flowrates than [5] and so capillary forces will be more important compared to viscous forces, this can have the effect of suppressing the development of viscous fingers.
- A 70 cm long, cylindrical sandpack was used in this study, with a diameter of 2.5 cm, compared to the slab geometry in [5], with thickness of ~2 cm, but a width of ~30 cm. This may affect the evolution of viscous fingers.

Although at the laboratory scale capillary pressure effects are important, at the field scale capillary pressure is less of an issue. The results from high rate flooding gave similar pressure transients and recovery for *all* floods, showing that the effects of pressure pulsing are less noticeable (where capillary pressure forces are small).

CONCLUSIONS

- Extensive measurements under single phase flow conditions have not found any situation where the flow rate could not be understood using Darcy's law based on unpulsed permeability data (provided pressure drops and flow rates are averaged).
 - Where enhanced single phase flow seems to occur, this is actually a result of an increased inlet pressure due to an additional pumping action from the pulsing device. When evaluating pulsed flow studies it is essential to plot the production rate against average pressure drop, rather than just to look at cumulative production against time.
 - Under two phase flow pulsing changed the character of water flooding. The capillary exit pressure was reduced and the total mobility of the fluids was increased. Recovery during the early stages of the pulsed water flood was reduced. These changes are consistent with pulsing making the core behave as if it were more "oil-wet" than the unpulsed waterflood.
 - The results from two-phase studies suggest that the effects of pressure pulsing may only be noticeable where capillary pressure effects are important. Capillary pressure effects in the field
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will only be significant some distance away from the well where viscous forces are lower. This would require the pulse to be propagated some distance away from the well (pulse source).

- Pulsing in two phase flow was found to improve the injected brine phase mobility only. For pulsing to be an effective IOR technique, the oil phase mobility must increase more significantly than the brine phase.
- The results from these laboratory tests do not in any way question any observations obtained in the field. The pulse workover technique may have benefits not related to these laboratory scale tests, e.g. the pressure wave causing changes to the near well reservoir architecture, or unblocking bridged perforations.

NOMENCLATURE

A	Cross-sectional area of core	q	Darcy flowrate
g	Acceleration due to gravity	t	Time
k_{pulse}	Permeability	$\Delta\rho$	Density difference (oil-air)
L	Length of core	μ	Viscosity
P_{in}	inlet pressure		
P_{out}	Outlet pressure		

ACKNOWLEDGEMENTS

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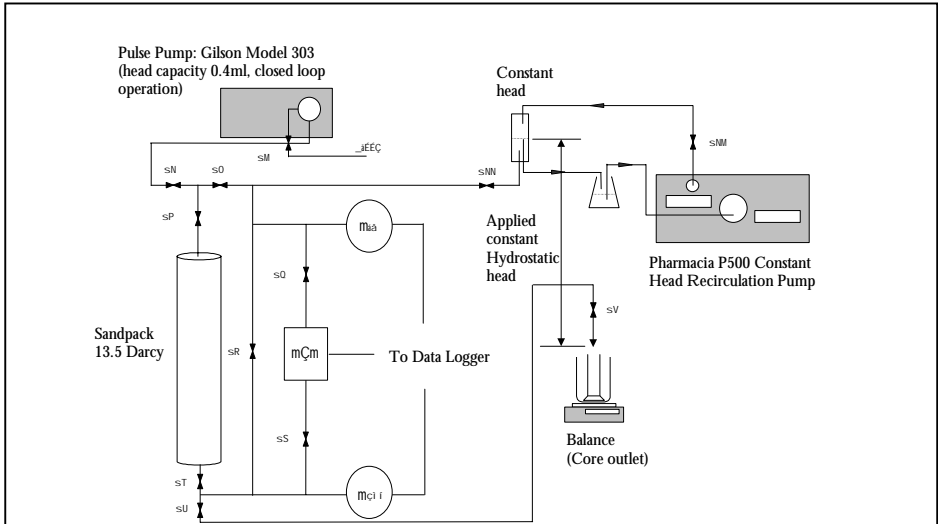


FIGURE 1: Flow Circuit with Uncoupled Pulse Device.

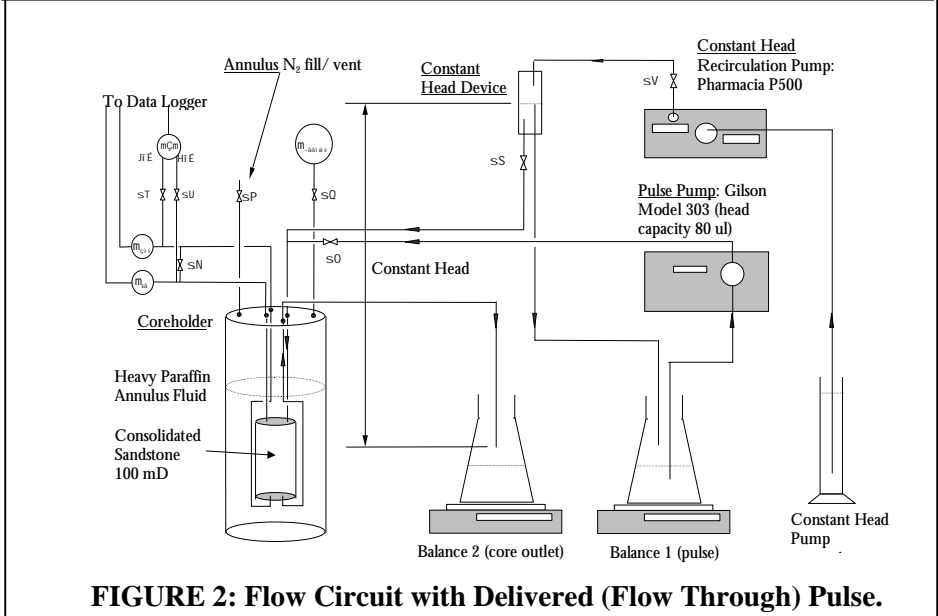


FIGURE 2: Flow Circuit with Delivered (Flow Through) Pulse.

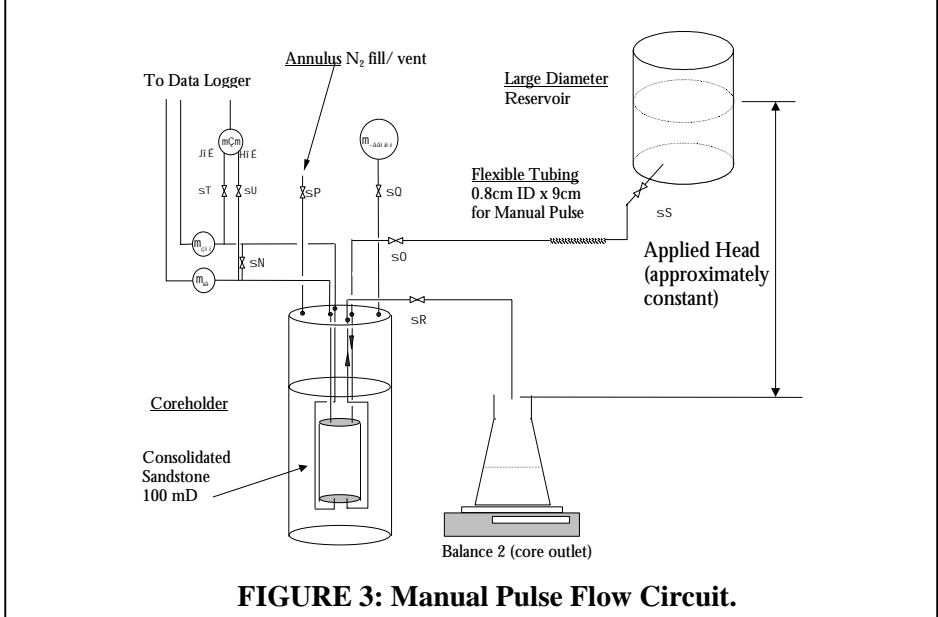


FIGURE 3: Manual Pulse Flow Circuit.

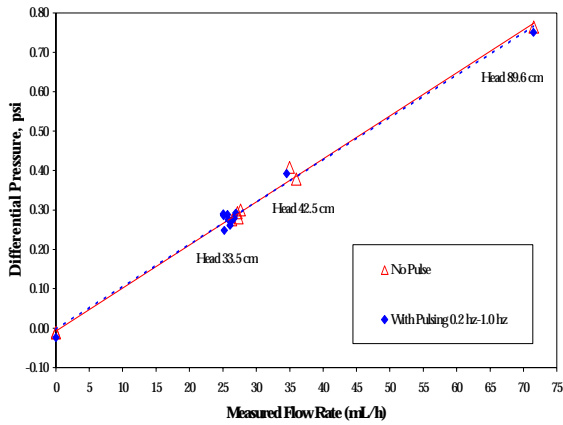


FIGURE 4: Measured Differential Pressure Vs Rate for 2.5 cp Oil.

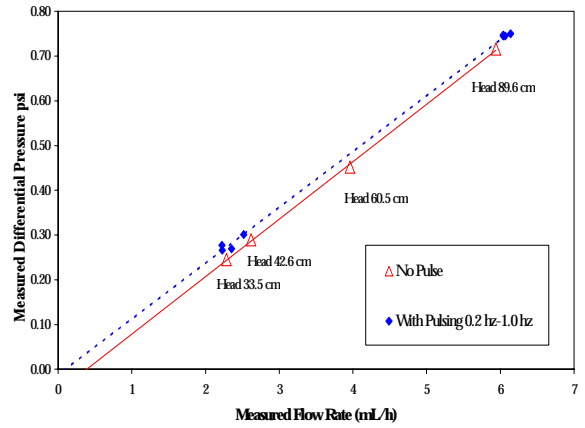


FIGURE 5: Measured Differential Pressure Vs Rate for 25 cp Oil.

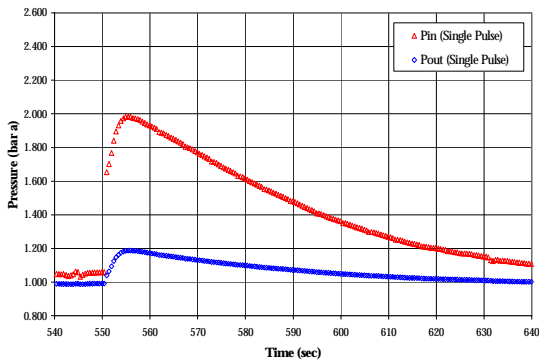


FIGURE 6: Pressure Transient from One Manual Pulse.

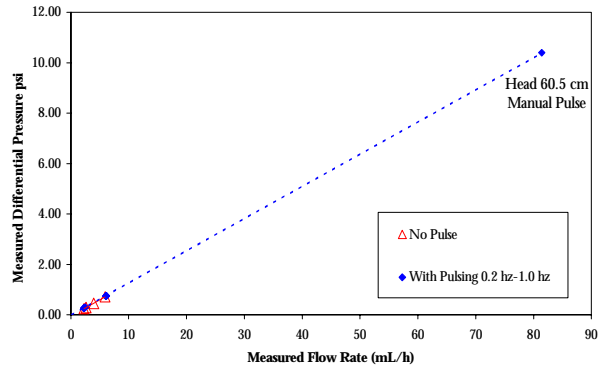


FIGURE 7: Differential Pressure Vs Rate for 25 cp Oil (including Manual Pulse Data).

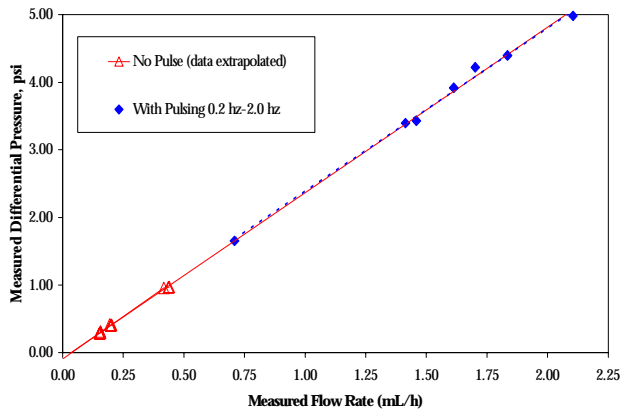


FIGURE 8: Differential Pressure Vs Rate for 25 cp Oil (using 100 md Core).

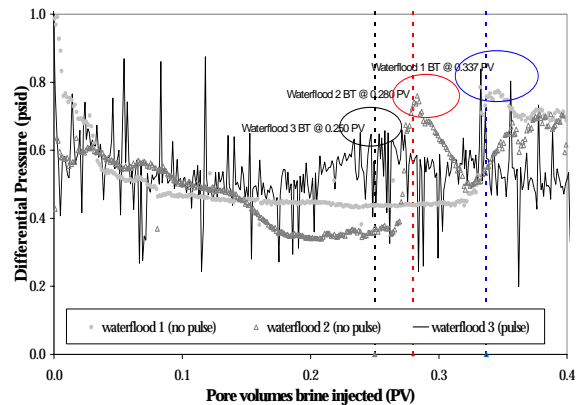


FIGURE 9: Breakthrough Pressure Transients.

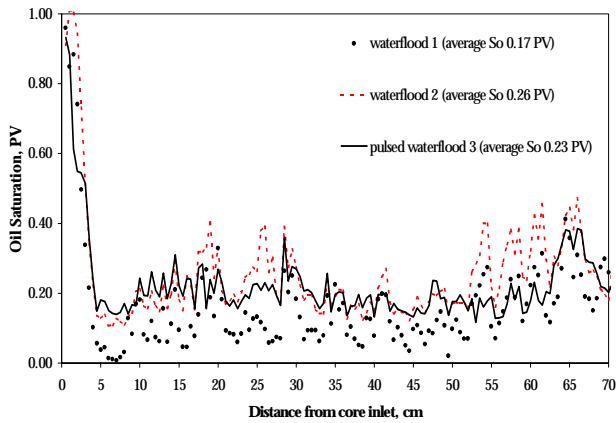


FIGURE 10: In-situ Oil Saturation and end of Low Rate Waterflood.

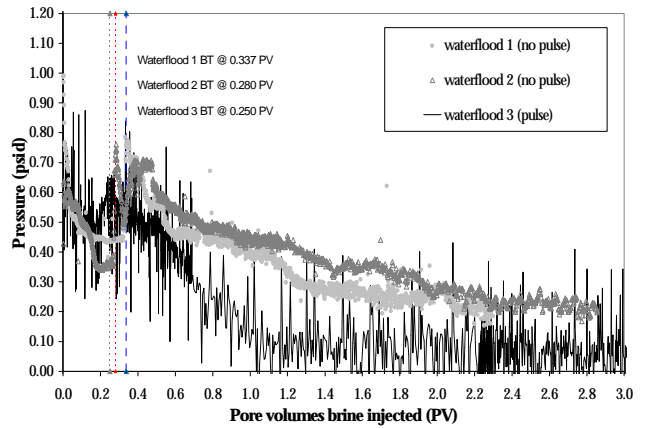


FIGURE 11: Measured Differential Pressure Low Rate Waterfloods.

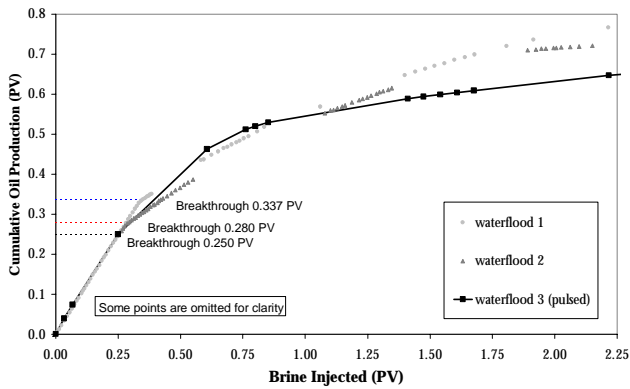


FIGURE 12: Oil Production Data Low Rate Waterfloods.

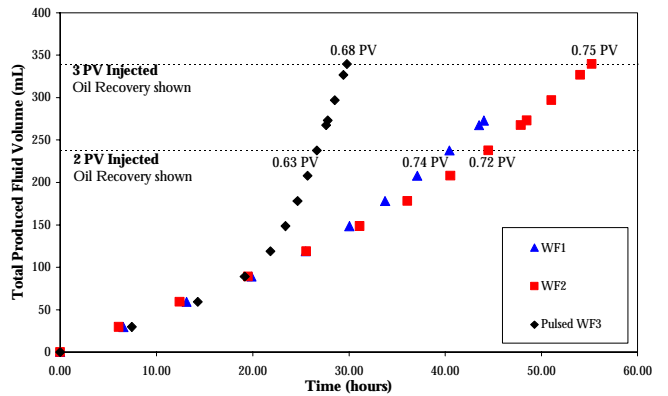


FIGURE 13: Total Produced Fluids Vs Time.

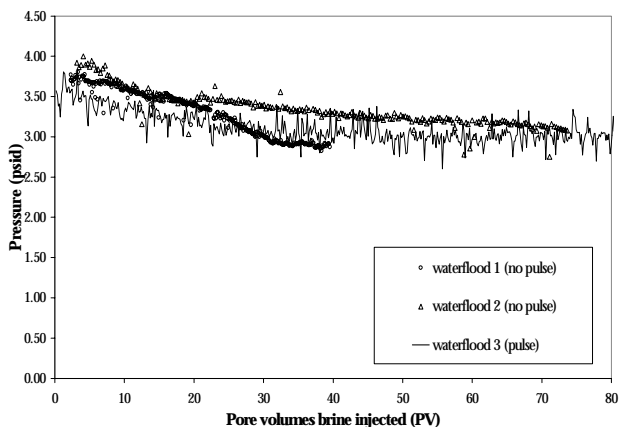


FIGURE 14: Measured Differential Pressure High Rate Waterflood.

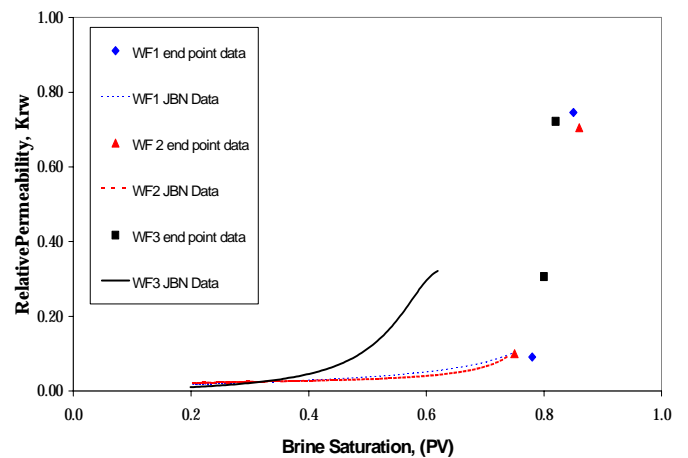


FIGURE 15: Calculated Brine Relative Permeability, k_{rw} .