Produced Water Re-Injection - Understanding the Problems

R.W. Paige and F.M. Sweeney

ABSTRACT

Studies carried out on the seawater injection facilities at a number of BP facilities have led to an understanding of the role of waterflood induced fractures and the effect of water quality upon well performance. In some areas seawater is now injected without fine filtration without any obvious effect upon injectivity. However, the risks associated with the re-injection of produced water are greater due to the higher oil and solids loading, and the different temperature regimes. Here, experience to date has shown that injectivity is both lower and in some instances its decline more rapid when compared with seawater injectors.

This paper will explore the role of waterflood induced fractures and the impact of water quality upon well injectivity. This will be supported by field data both from seawater and produced water facilities.

INTRODUCTION

Until recently, the flow of water away from an injection well into the formation was assumed to be in a radial manner. The flow entering the formation would therefore pass through a small area of rock face when entering the formation and the control of water quality was seen as vital in preserving the injectivity of a well. Specifications for the filtration of injected water have frequently been set based on the need to prevent plugging of the formation by suspended fine solids and oil droplets.

These specifications were determined from laboratory studies using core-plugs. Cores were flooded and the change in core permeability as a function of solids loading (concentration and particle size) was measured. In addition to standard core-flood studies, mercury porosimetry was used to measure the pore size distribution within the core. From these measurements the effective hydraulic radius was obtained which could be used as an indication of the particle sizes that would tend to plug the rock. Using this information, a filtration requirement was specified for seawater injection.

For Forties, the design specification was 95% removal of particles greater than 5µm in diameter, with 100% removal of particles larger than 10µm. This was based on a 20µm hydraulic radius. For other fields the specification was even more stringent; Ula - 95% removal > 2µm. As a result of these strict injection
specifications, large and costly water filtration units were installed to protect the reservoir from damage.

**Seawater filtration experience**

Over the last 5 years however, our experience in water injection has cast doubt upon the need for such stringent filtration specifications. This is supported by the experience of other operators; for example Beryl and Statfjord do not fine filter the seawater prior to injection.

In order to determine whether fine filtration was needed in all cases, a series of water quality measurements were made on a number of BP operated platforms in the North sea. Two such studies were carried out on the Forties Charlie and Ula platforms. Water quality measurements were carried out at different points throughout the injection system; at the seawater winning pumps, upstream and downstream of the fine filters, the wellhead manifold and downhole. A schematic of a typical seawater injection facility is shown in figure 1.

![Diagram of seawater injection system]

**Figure 1**  
**Ula Water Injection System**

The results of the gravimetric analysis of suspended solids throughout the Forties Charlie system are detailed below. These data show that the fine filters do indeed operate effectively, reducing the overall solids loading (Figure 2). However, the downhole samples show a dramatic rise in the solids loading. These values are 10 times higher than the raw seawater intake itself.
Figure 2  Total Suspended Solids in Forties Charlie Injection Water

As a result of this study, the fine filters were bypassed and the water quality measurements repeated. These data showed that filtration had a negligible effect on downhole water quality. Removal of the fine filters did not lead to an increase in solids loading, and additionally did not lead to any reduction in injectivity during the period of the measurement.

This indicated that in many cases the downhole water quality is worse than the intake water quality, even when the fine filtration facilities are working effectively. The conclusion from this was that fine filtering seawater is often unnecessary, and as a result led to the bypassing of these facilities on the Forties, Ula and Gyda platforms in the North Sea.

Waterflood Induced Fractures

The field results confirmed previous suspicions that the laboratory derived water injection specifications were too stringent, particularly as the actual injected water quality would suggest significant permeability damage. The explanation for the tolerance of the formation to poor water quality is the role played by fractures induced by the injection process.

Fracturing occurs when the bottom hole pressure in the reservoir exceeds the compressive stress in the formation rock. Typically the formation breakdown gradients lie in the range 0.7-0.8 psi/ft, which would normally exceed the injection pressure gradient; for example the operator might inject at an injection gradient of 0.6 psi/ft. However, when cold water is injected into a warmer reservoir, the reservoir is cooled and contraction of the formation will result. This will cause a reduction in the compressive stresses, which will lower the pressure needed to fracture the formation (possibly by 0.2 psi/ft in a consolidated sandstone). Hence many wells were being “accidentally” fractured.

These thermally induced fractures play a significant part in the injection water quality argument. The presence of the fractures provides a much larger surface area for leak-off, than an non-fractured system. This coupled with the ability of
fractures to propagate, creating fresh fracture faces for fluid leak-off, are the major reasons for the tolerance of injectors to poor water quality.

**Fracture Measurement**

The presence of fractures in injectors was confirmed by the use of Hydraulic Impedance Testing (HIT). This is a method for detecting and measuring fractures. The method works by introducing a pressure pulse into the wellbore and monitoring and interpreting the pressure response at the wellhead.

The pulse is typically initiated by rapidly opening and closing a valve connected to the wellhead. A pressure pulse travels down the wellbore and is reflected at various points along its path. Figure 3 shows several idealised HIT pressure traces.

![Fracture Measurement Diagram](image)

**Figure 3**  
*Hydraulic Impedance Test Pressure Traces for Various Fracture Sizes*

The first trace shows the pressure response for a non-fractured, constant diameter wellbore. The pressure pulse travels up and down the wellbore, being reflected at each end and is attenuated slowly. When a small fracture is created the reflection from the bottom is reduced and energy is transmitted into the fracture. In this sequence the pulse which travels into the fracture is assumed to decay to nothing and thus is not seen again in the wellbore. As a result the decay of the main pulse is effectively increased. As the fracture size is increased the reflection coefficient moves to zero and no reflection occurs. As the fracture grows further, this leads to the reflection of an inverted peak. This
grows with increasing fracture growth, and thus the decay of the pulse becomes less rapid.

To date, over 50 injectors have been tested using HIT in Europe and North America. In all cases they have been found to be fractured to differing extents.

Field observations provide further support for the presence of thermally induced fractures and their influence upon injectivity. The plot shown in Figure 4 shows the increase in injectivity which occurred on a Ula injection well when a production shutdown resulted in a reduced seawater injection temperature. Prior to this event, the seawater was used for process cooling and hence was heated before being injected.

![Figure 4](image)

**Figure 4** Performance of Ula Well A-04 During Large Temperature Change

The increase in injectivity is caused by the growth in fracture size as a result of the increased cooling effect. This is exemplified further in figure 5, where for a fractured injection well, the injection pressure required to inject at constant flow rate gradually reduces as the formation is cooled.

![Figure 5](image)

**Figure 5** Bottom Hole Temperature and Pressure Measured During the Start-up of a North Sea Injector - Injection Rate 10,000 B/D
Revised Seawater Injection Specifications

The evidence presented in the previous sections has led to a greater recognition and better understanding of the role of waterflood induced fractures. This improved understanding of water injection processes together with field studies have shown that in many cases fine filtration of seawater is unnecessary.

However, this will not apply in all cases and as each reservoir must be looked at individually. In particular, the examples cited above are all North sea operations were the source water quality is already good, ie low solids loading, < 1mg/l, with only occasional excursions during bloom periods, <5mg/l. A good example to exemplify the problem is Wytch Farm. Here the source water is taken from Poole Harbour at an intake depth of 12m. A consequence of this is the very high solids loading, which is exacerbated further by tidal effects (solids loading > 20mg/l). Such a high solids content in the source water stream may therefore require fine filtration.

As a result of the field studies carried out and the supporting technical evidence, guidelines for seawater injection were produced. These indicated that for typical North Sea seawater injection operations, into reservoirs with permeabilities greater than 50mD, solids loading at the sandface less than 10mg/l will not effect injectivity significantly. As a result, fine filtration was not thought to be an essential pre-requisite for injection.

PRODUCED WATER RE-INJECTION

As a consequence of the seawater injection studies, a more detailed investigation of the impact of produced water re-injection (PWR!) was initiated. There were several good reasons for this. As fields mature, the volumes of produced water requiring disposal tend to increase, and so it is essential to adopt the most efficient and environmentally sound disposal system. To illustrate the potential problem the oil and water production profiles for Forties are presented in Figure 6.

Figure 6 Production and Injection Profiles for Forties Field
However due to field management changes, i.e. use of gas lift etc., water rates considerably higher than initially envisaged are now being produced from several of our fields. This has added significantly to the costs of handling produced water (water treatment handling limitations, equipment upgrades and retrofits).

In addition, environmental pressures are likely to force oil in water discharge limits down in the North Sea. In the Gulf of Mexico, the discharge limits have already been reduced to 25 mg/l. Limits of below 20 mg/l oil will cause a rapid escalation in cost as more expensive technology e.g. Filter/Coalescers, Centrifuges and Membranes, are required in place of Flotation and Hydrocyclones. This has added further to the need to be able to effectively re-inject the ever increasing water volumes.

**BP’s Current Position**

Currently BP’s water production worldwide exceeds a million barrels per day, and this is expected to rise considerably before the turn of the century. Until recently in the North Sea, the majority of this water was treated using conventional treatment units to reduce the oil content to below 40 mg/l prior to discharge. Re-injection is potentially a more attractive option from an environmental viewpoint, but if it is to become the preferred alternative for water disposal, re-injection must also be economically competitive and not incur excessive risk.

To this end a study was carried out to compare the economics of produced water re-injection with other options for water disposal. Figure 7 illustrates the costs and relative performance of the different technologies compared with produced water re-injection.

![Figure 7: Costs and Performance of Water Disposal Options](image-url)
This study showed that for new field installations, the cost of re-injecting produced water were comparable to the cheapest options for water treatment to existing discharge specifications. If legislation requires further reductions in oil discharge levels, the costs move more in favour of re-injection. For existing installations, re-injection may also be a cost effective solution where upgrading facilities is required to handle increasing volumes of produced water.

Although the economics may lie in favour of re-injection, a major concern must be the difficulty in predicting well performance when re-injecting produced water. In conjunction with the economic evaluation, studies have been ongoing at a number of BP operating areas looking at the field and reservoir effects of produced water re-injection. This has provided much of the information to support the economic assessment made, but more importantly has provided an insight into the major mechanisms that influence produced water re-injection and ultimately well and reservoir performance.

**Produced water Re-Injection- Field Studies**

The fact that seawater could often be injected without the need for fine filtration begs the question of how dirty can the water be before it impacts well injectivity. This is not a new phenomenon, as disposal wells routinely inject very dirty waters, and have done successfully for very long periods. Indeed BP has experience of such disposal wells both at Wytch Farm and Prudhoe Bay.

However, if the water being re-injected is part of the voidage replacement (secondary oil recovery) strategy, it is vital to ensure that PWRI does not detrimentally effect oil recovery from the reservoir. This may be a critical factor in an offshore environment, particularly for platforms which are well slot limited. As such injectivity must be maximised from its current injection wells.

**Forties PWRI**

To address these impacts a trial was initiated on the Forties Delta platform in 1989. A separate produced water injection header was added alongside the existing seawater injection header, and one pair of injection pumps dedicated to PWRI (Figure 8). Water from the main separator is fed to a degassing tank, and there split between PWRI and conventional flotation unit treatment for disposal overboard. From the degassing tank the water is injected directly downhole without any further treatment. As a result of this the water quality is generally poor.
Prior to the start of the PWRI trial, the target well (FD5-1), injected 25mbd seawater at 90bar whip. After the first 6 months injection, it was concluded that PWRI had resulted in a 20% loss of injectivity, compared with previously injected seawater. This was judged to be caused by a large skin and not by any inability of the reservoir to take the produced water. This led to an extension of PWRI to other Forties platforms. Two alpha wells were converted from seawater to produced water injection, and a dead producer was converted to PWRI. After only six months of operation, the alpha well losses were all greater than that experienced in the delta pilot, with injectivity losses of approximately 40% relative to seawater.

The following plot (Figure 9) shows the typical decline in injectivity profile for a Forties alpha well injecting produced water.

There are a number of possible reasons for the losses of injectivity, several of which will be discussed in later sections. One major factor could be the water quality itself. The alpha wells have experienced higher losses of injectivity compared with the delta well over a similar time period. On alpha both the oil and solids loading in the produced water are higher than that for delta (typically about 3 times).
One of the main causes of the increased solids loading on alpha has been attributed to the use of electric submersible pumps (ESP's) on Forties echo; a satellite platform feeding into the main forties alpha separation/treatment facilities. In addition, slugging problems from Echo to Alpha in the subsea pipeline have exacerbated the problem of maintaining good quality water in the alpha separation facilities.

**Wytch Farm PWRI**

The impact of water quality upon injectivity can be further exemplified using data from another BP operated field - Wytch Farm. At Wytch farm, the produced water from the separators is initially degassed, and the oil and solids content reduced using pressurised backwashable sandfilters. In these units the oil and solids content is typically reduced down to <15mg/l oil and < 5mg/l solids. Due to its location all the produced water is re-injected - currently some 40mbd. Figure 10 shows the injection profile for a typical Wytch farm well, with virtually no loss of injectivity measurable over a similar period to that shown for the Forties alpha well.

![Graph showing flow and pressure over time](image)

**Figure 10  Produced Water Injected into Wytch Farm Well**

Comparing the profiles in Figures 9 and 10 for Forties and Wytch farm respectively, the data suggests that cleaning up the produced water will permit relatively trouble free injection. However, treatment plants are expensive as discussed earlier and therefore it is essential to establish the level of clean-up required to achieve acceptable injectivity.

**Issues Impacting PWRI**

There are several key issues that need to be investigated before a complete understanding of the mechanisms taking place during PWRI can be achieved.
Plugging Mechanisms

In the same way that the seawater injectors discussed in the earlier sections were fractured, so are the produced water re-injection wells. This has been confirmed by HIT analysis, PFO tests and thermal fracture simulation. However, as produced water is normally hotter than seawater, the injectivity of produced water injectors tends to be lower, as fractures tend to be smaller. In addition the amount and nature of any solids in the produced water can have a significant impact on well injectivity. This appears to be borne out from the comparative water quality study for Wytch Farm and Forties wells.

However, where are these solids going? Not all of the particulates pass into the rock matrix; this can be born out by the observation of sludge extrusion from fractures following wells being shut-in. Ultimately the fate of the particles whether they pass into the formation (possibly causing permeability problems), or not is likely to be size dependant. To that extent it is important to understand the mechanisms of transport of the particulates through the fractures and its impact on fracture growth. This knowledge will help in the design of future PWRI systems and also remedial well treatments.

Effect of Temperature

There has been considerable debate as to the influence of temperature upon well injectivity. In principle a hotter fluid will have a lower viscosity and therefore injectivity should be greater. However, conversion of a seawater injector to PWRI in general reduces injectivity, with the rate of injectivity declining fairly rapid in the first few days, until an equilibrium state is achieved.

To test the thermal effects on the injectivity of a well, a forties PWRI well was converted back to seawater injection. The injection rate immediately rose by 50% and gradually increased further throughout the 2 week injection period to about 95% of the original seawater rate. On re-conversion back to produced water injection, the rate declined to previous (produced water) levels after 2 weeks.

Remedial Treatments

In the early stages of the Forties delta PWRI project, an event occurred which stimulated injectivity of the well. The stimulation was caused by 2bbls of partially spent acid from a routine well service operation entering the production water injection system. It had the effect of increasing the PWRI rate while decreasing the injection pressure. Further acid stimulations were then performed which increased injectivity above original seawater performance (Figure 11).
Figure 11  Acid Stimulation Improve Forties Delta Produced Water Injectivity

These stimulations were short lived, and within about a month, injectivity had returned to previous levels. This suggested that a significant proportion of the material entering the well was acid soluble. Subsequent analysis showed that 50% of the produced solids was most likely derived from carbonate scale. It had always been recognised that the Forties produced fluids were naturally scaling with respect to calcite and barite. To this end scale inhibitors were deployed to control scale formation, although it should be noted that these chemicals only affect the rate kinetics of the reaction. The plugging potential of scale has been evidenced further recently when the scale inhibitor injected into the PWRI system was not operational. A much greater loss of injectivity was observed during that period before the problem was identified and the inhibitor dosing re-commissioned.

Several other stimulation treatments have been assessed on Forties; a surfactant and a mutual solvent. Both of these treatments showed little sustained response suggesting that neither oil or a change in wettability is the cause of the injectivity decline on Forties. However, more effective stimulation treatments have been carried out in some other BP operated areas.

Summary and Future Plans

As detailed in the previous sections, PWRI is both an environmentally acceptable and economic alternative, particularly for new field developments, but also for existing platforms where major water treatment expansions are required. However there are some issues that need to be considered. In the main, the injection of produced water results in a lower injectivity compared with seawater. In addition, part of the loss of injectivity is linked to the water quality itself, i.e. the degree of particulates in the produced water.
Summarising BP position on PWRI in the UK, Forties delta has experienced a 50% injectivity loss in 4yrs, whilst alpha has suffered the same loss in only 18 months. This difference is seen to be attributable to the differing water qualities for the two platforms; higher solids and oil contents. Both of these platforms are injecting untreated produced water directly from the separator. However, at Wytch Farm where the water is treated to levels within conventional offshore discharge limits, no loss of injectivity has been observed.

Where losses of injectivity have occurred, stimulation treatments have not been widely successful. The most effective, albeit for short time periods is acidisation. However the damage resulting in the loss of injectivity does not appear to be permanent, with near total recovery upon re-conversion back to seawater injection.

Over the next couple of years work will continue to address the plugging mechanisms of particulates and their impact on fracture propagation. This will help to identify the degree of water clean-up required in order to minimise injectivity loss. In addition the impact of cooling PW will be assessed as well as higher WHIP's to maintain initial injection rates during PWRI.