

A Comparative Analysis of a Relative Permeability Modifier and Direxit Resin for Shutting Off Water Production

April 3, 2003

Executive Summary

A large Canadian Oil and Gas company has produced oil from a heavy oil reservoir for four years. Some of the wells are reaching an economic limit due to very high water cut and a decision must be made to either treat the wells to reduce water cut or abandon the producing wells. There is a significant economic advantage to shut water off in the wells as opposed to other alternatives.

Hycal Energy Research was requested by the company to perform experimentation in order to compare the water shut-off capabilities of a novel relative permeability modifier (RPM) and Direxit resin using available core from well x-yy-zz-8W4, interval 943 to 951 meters.

After comparative testing, using linear core stacks, with the two products, Direxit resin proved to be more efficient at reducing water permeability than the RPM: **Direxit reduced water permeability by a factor of 70 whereas the RPM reduced water permeability by only 30%.** This conclusion is based upon direct comparison of end point permeability to water after the secondary water flood and the end point permeability to water after the shut-off treatments. The RPM was applied to one core stack and Direxit was applied to a separate core stack.

The RPM was very effective at recovering more oil during the RPM injection phase (7.5 PV): the RPM recovered an additional 31.5% OOIP. This oil recovery increased the water saturation and therefore the end point permeability to water was higher than after the secondary water flood. However, for purposes of the residual resistance factor (RRF) calculation, the baseline water permeability after water flood was used (not the permeability to the RPM itself).

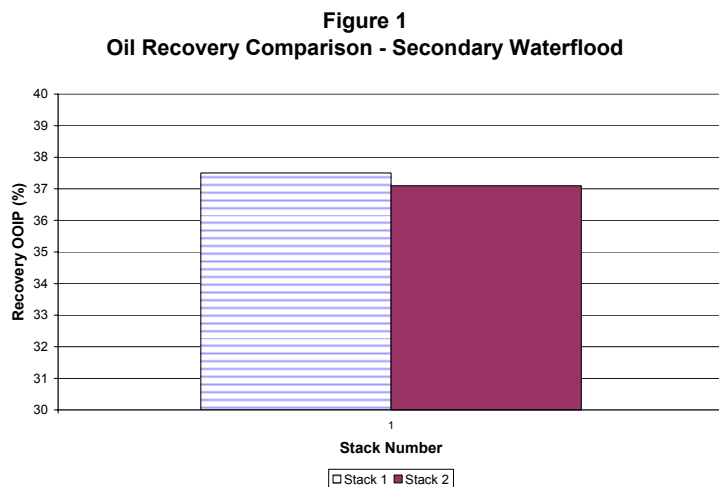
The oil recovery during the Direxit application (1.5 PV) was minimal. However, once post-treatment water injection was commenced an additional 32.8% of OOIP was produced.

The oil permeability decreased by a factor of 2.32 after the RPM treatment. However, during the oil flush, 30% PV of water/RPM was produced accompanied by a concomitant increase in oil saturation. This served to increase the end point to oil; oil was able to flow through the porous features that were previously filled with the RPM. This effect results in a superior RRF to oil response for the RPM compared to Direxit.

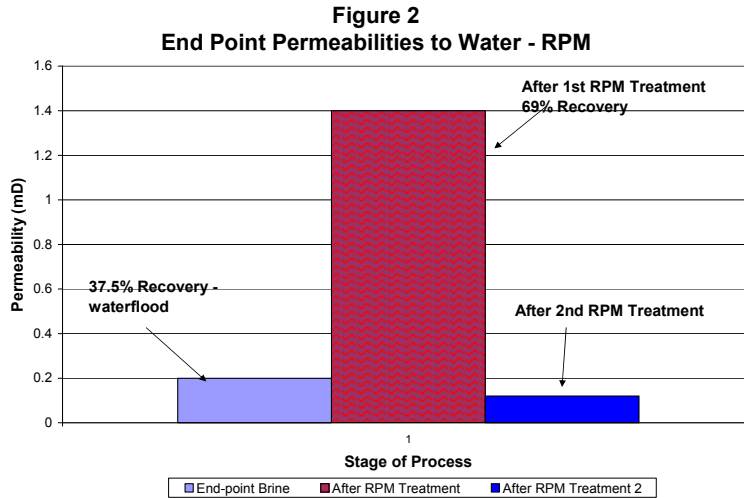
The oil permeability after the Direxit treatment was reduced by a factor of 40 times since the conduits previously conducting water were now blocked and the overall porous features available for flow were much smaller (Sor of 22.5% associated mainly with the smaller porous features of the core). If the interfacial tension of the water and oil was sufficiently low to access the porous features still filled with oil, a significant portion of this bypassed oil could possibly be recovered.

Results and Discussion

Initially, the core stacks were flooded with oil until a stable differential pressure was achieved and the oil fraction was 1.00. A water flood using field injection water was then conducted. Figure 1 shows the comparison between the water flood recoveries on the two core stacks. The water flood recovery was very comparable indicating the similarity of the core stacks used.



After the water flood was completed, the end point water permeability was measured. This became the baseline for comparison since this state corresponds to the current field scenario. Figure 2 shows the performance of the RPM compared to the endpoint water permeability at the end of the water flood.



The RPM was not very effective at reducing water production rates, reducing water permeability by about 30%. Figure 3 shows the same data but includes the permeability to the RPM itself, since during the RPM injection (7.5 PV) the RPM exhibited an end point permeability of 10.5 mD. Compared to the RPM permeability the post-test water permeability was low but compared to the water flood permeability the post-test water permeabilities were not significantly lower.

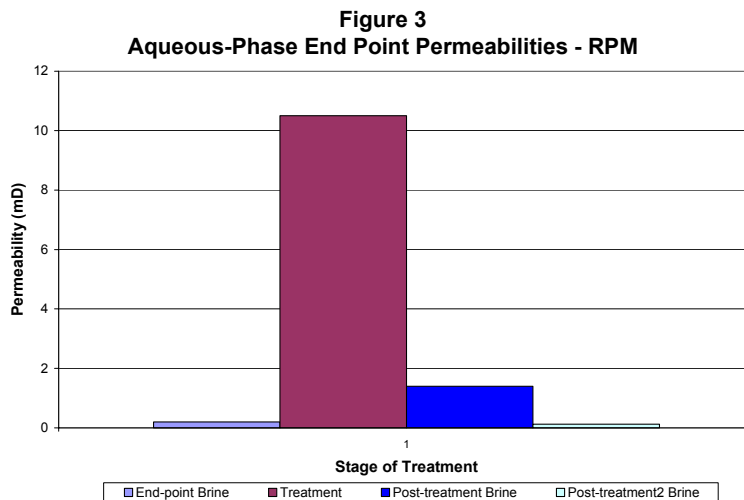
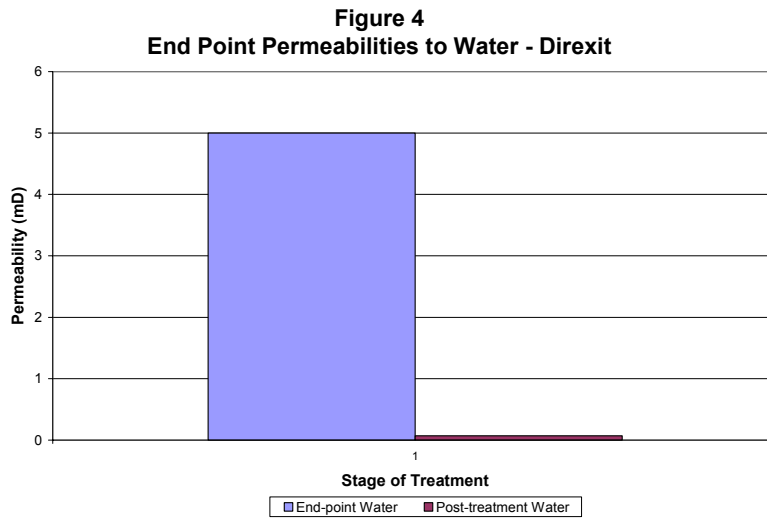


Figure 4 shows the water permeability data for the Direxit system on a separate core stack. The Direxit was efficient at reducing water permeability.



The RPM recovered incremental oil during the placement of the treatment (31.5% OOIP) whereas the Direxit produced oil after the treatment during the post-treatment water flood (32.8% OOIP).

Figure 5 and 6 show the results of the oil permeability decrease. The RPM shows only a factor of 2.32 decrease in oil permeability since during the oil re-saturation over 30% of the RPM/water is produced (the portions of the core previously conducting water). Direxit showed a severe decrease in oil permeability since the conduits for water flow, the higher permeability porous features, were blocked. Since Direxit sets as a solid it is not able to be produced when the oil re-saturation step occurs and therefore the permeability to oil is significantly lower. By this time however the residual oil saturation is down to 22.5%.

Figure 5
Oil-Phase Permeabilities - RPM

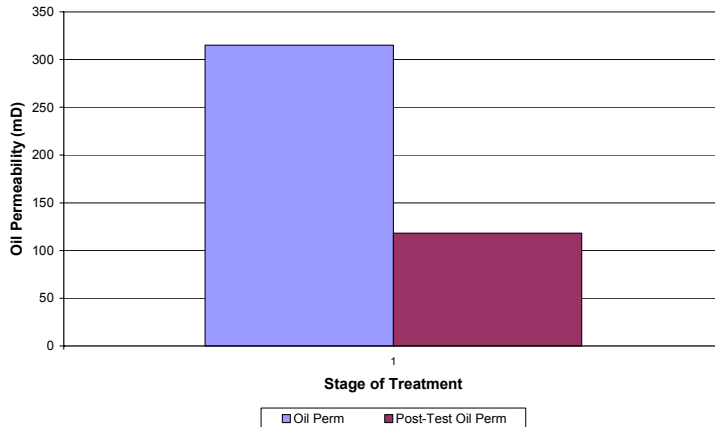
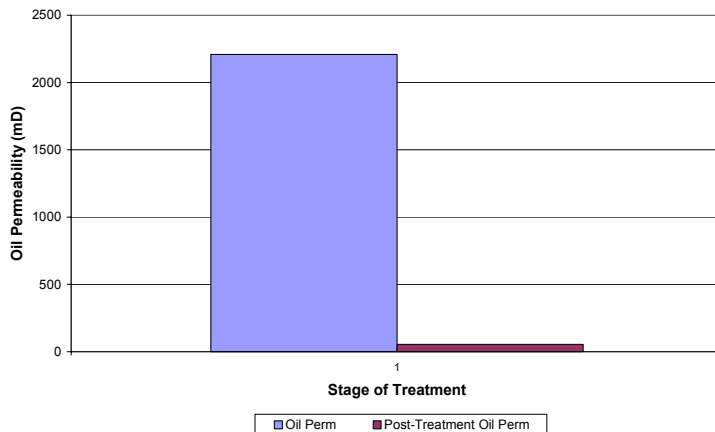
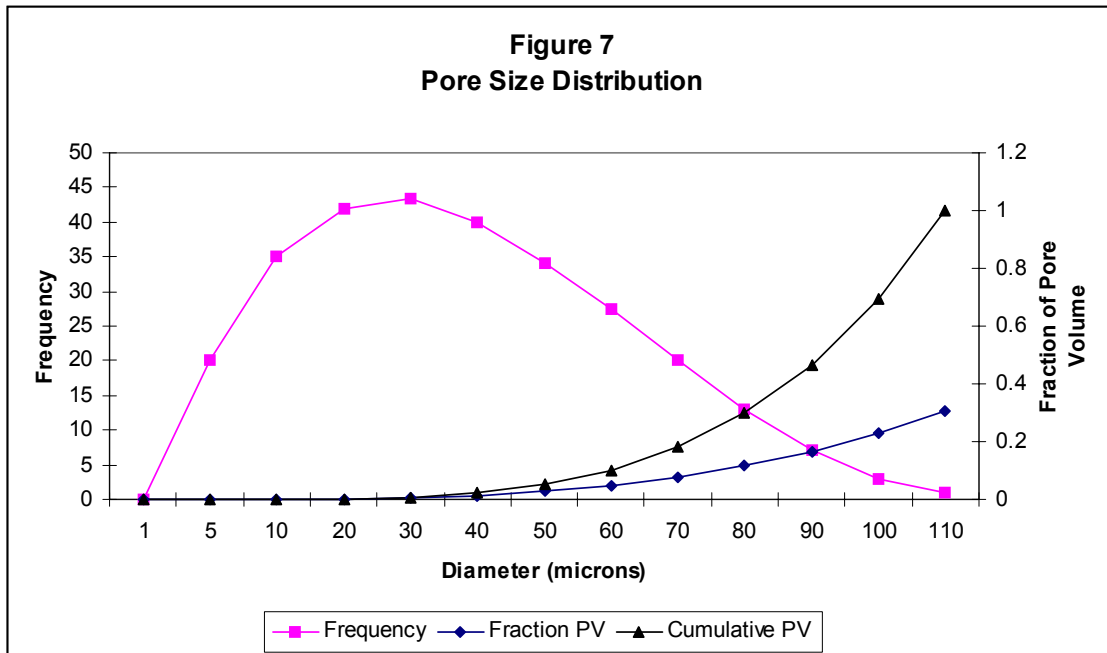


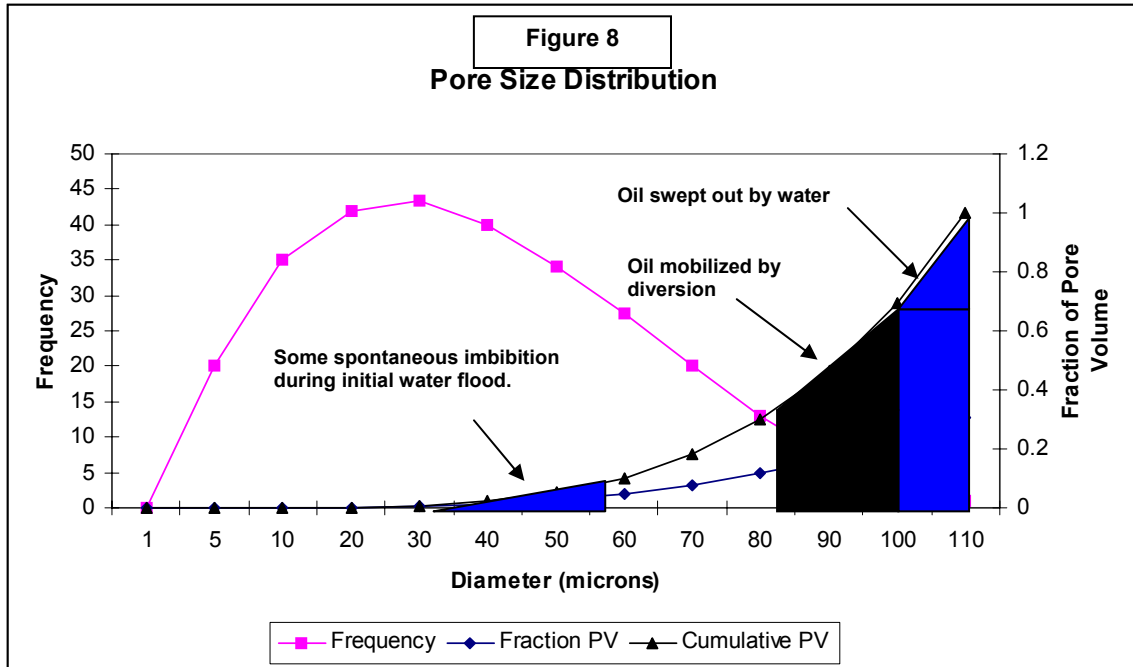
Figure 6
Oil-Phase Permeabilities - Dixelit



This phenomenon of shut off is shown in figures 7 and 8. Figure 7 shows the theoretical pore size distribution as frequency of porous features as well as incremental and cumulative pore volume based on a spherical-pore assumption. Figure 8 shows the portions of the core that would be expected to be swept on initial water flood (Blue) followed by the incremental oil recovery with the diversion chemistries. When the oil is used to re-saturate the rock, in the case of the RPM, the black would be expected to flow back. Indeed, the water/RPM recovered during the oil re-saturation step was almost the same as the incremental oil recovery after the RPM (31.5% oil recovery versus 30.6% water/RPM recovery). Thus the oil permeability only 2.32 times lower than the initial oil permeability.

With Direxit, the blue zones are filled with the resin which becomes a solid. There is therefore no flow through this portion of the rock. Since permeability may be assumed to be roughly proportional to the square of diameter of the porous media apertures the rock after Direxit will have a totally different absolute permeability (the once larger porous features that were previously available for flow are rendered non-porous). This serves to greatly reduce flow through the high water-saturated zones and to divert flow from the water-filled pores to previously-bypassed oil – thus the incremental recovery. However, the absolute permeability of the formation has been modified and thus the reduction in oil permeability. From a field perspective this reduction in absolute permeability may be a desired effect with conformance-control chemistry where the high-flow conduits are rendered ineffective and previously by-passed oil is recovered. Further discussion is beyond the scope of this report since the vagaries of reservoir mechanisms may impact whether the reduction in absolute permeability is beneficial or detrimental.





The calculation of residual resistance factors (RRF) is a common method for comparing water shut-off strategies. The RRF is defined as the ratio of initial permeability of phase A to the permeability of phase A after the treatment. Figures 9 through 12 show the RRF values for the different applications investigated as part of this work. The results are as reported above.

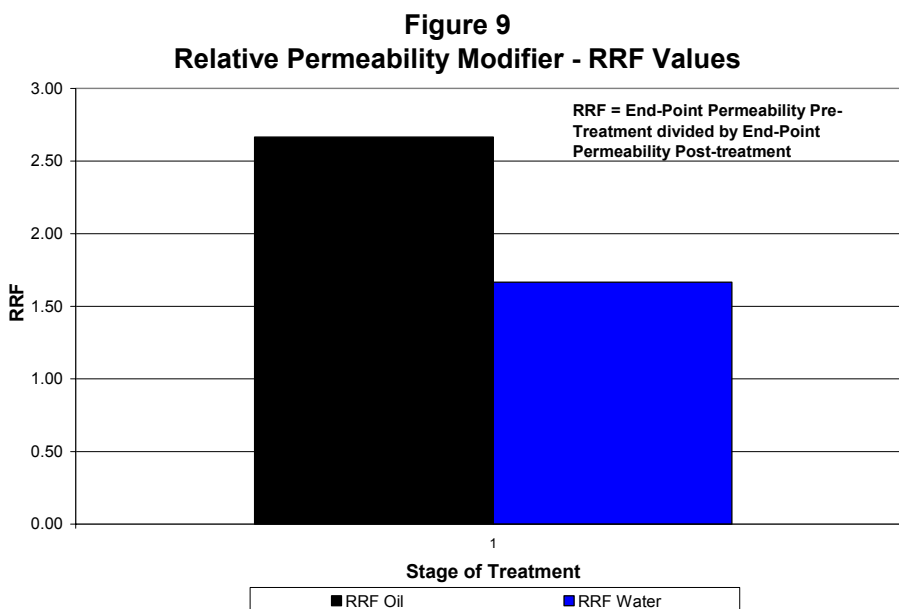


Figure 10
Direxit RRF Values

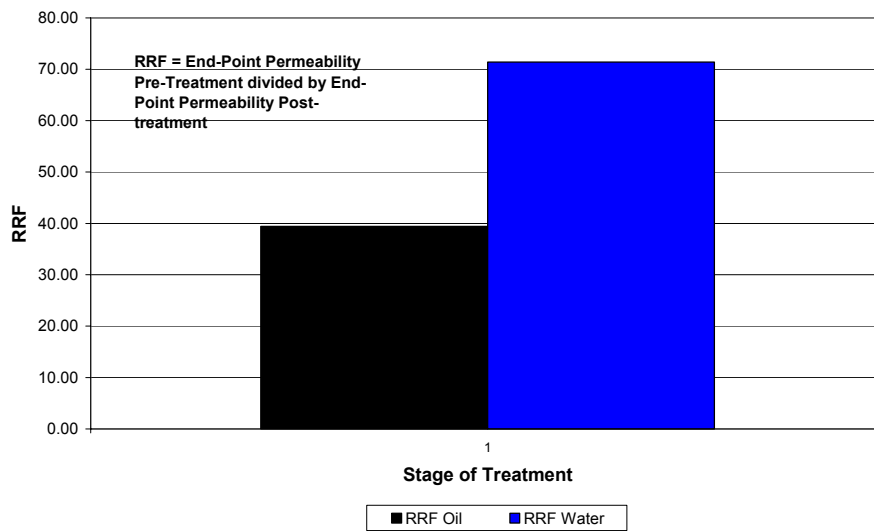


Figure 11
RRF Oil Comparison

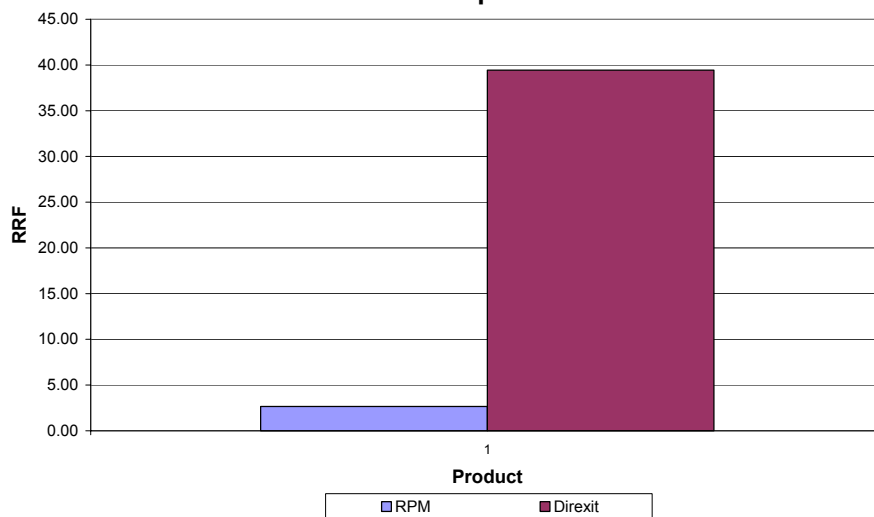
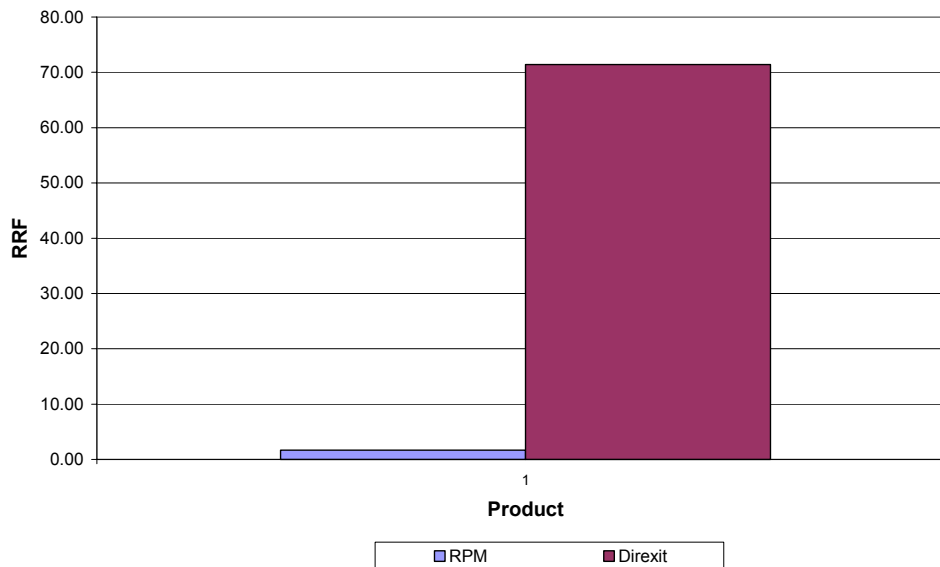


Figure 12
RRF Water Comparison



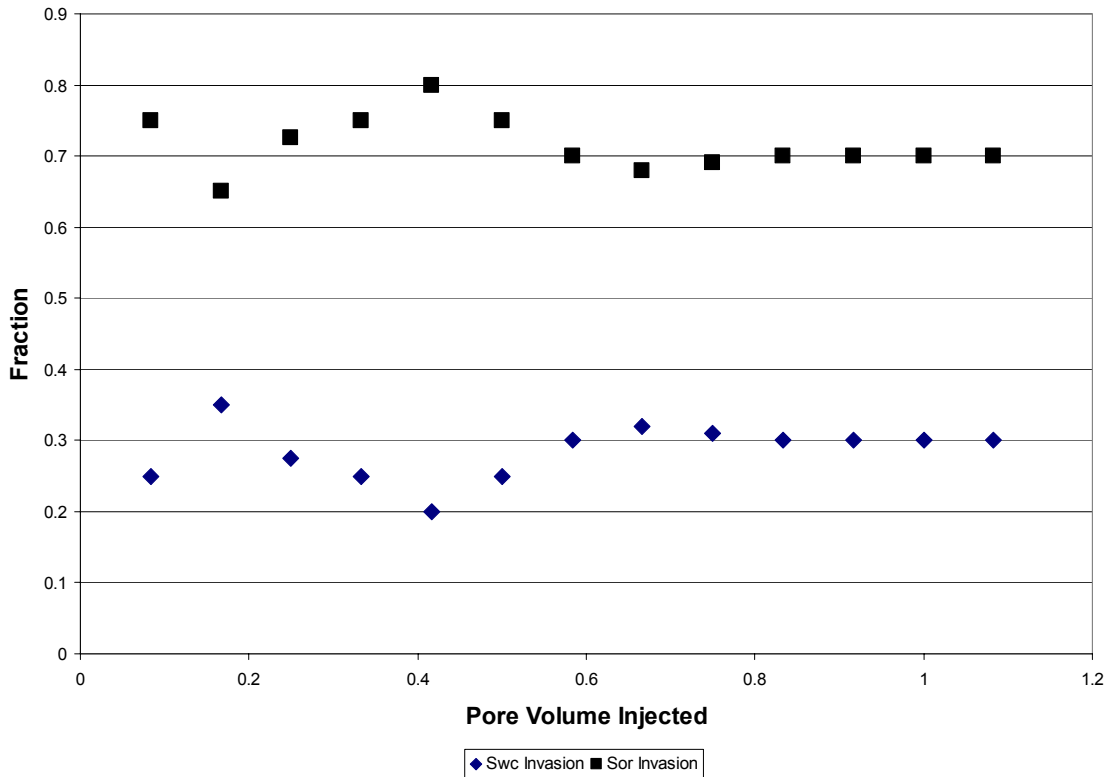
Future Application Considerations

One point of frequent concern with chemistry that is classified as non-selective is the likelihood of invading all of the porous features and rendering the porous structure unproductive. Previous testing at Hycal Energy Research has indicated that six parameters may play a very important role in water shut-off applications. The six parameters are: phase behavior, interfacial tension, viscosity ratio, pore size distribution, wettability and gravity. Each of these parameters can be used to optimize the design of shut-off treatments. For example, with porous media that exhibit a large spontaneous imbibition index a more viscous treatment may be desirable to retard the rate at which, and the depth to which, the treatment enters the rock. Hycal has found that selectivity of placement can be significantly enhanced by controlling the rate at which the treatment is pumped. This is done in the field by the use of fluid control equipment such as control valves, cement retainers and injection pump operation.

In the laboratory a simple system of two parallel core stacks was assembled and a water flood was conducted. Almost all the recovery was

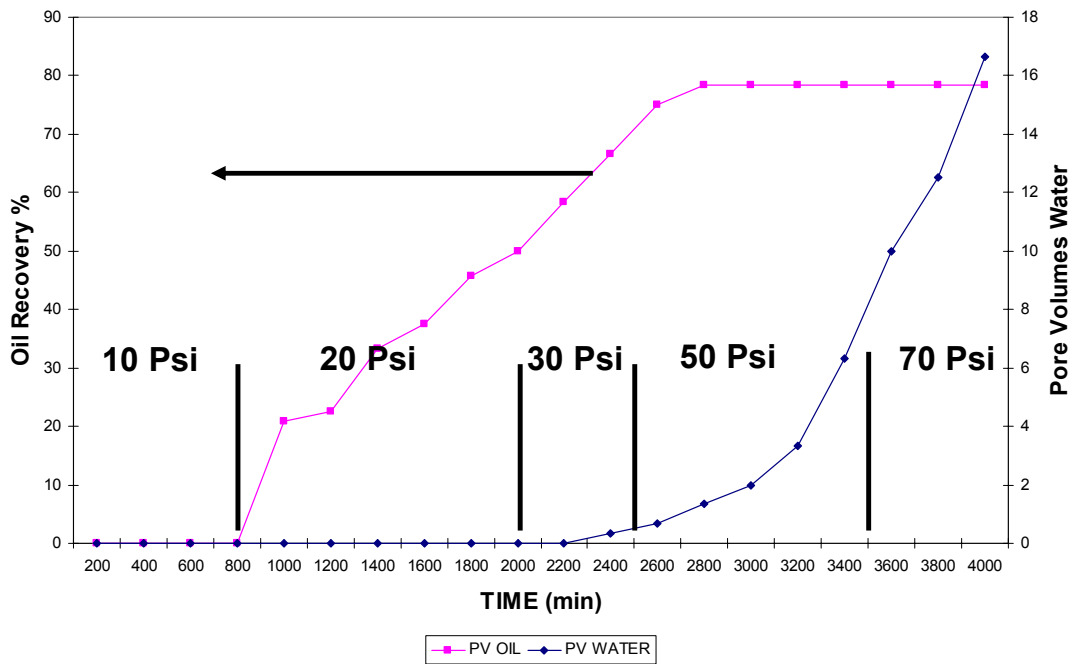
from the high permeability stack (approximately 10:1 absolute permeability ratio between the stacks); the high-permeability stack resulted in 70% oil recovery and the low-permeability stack exhibited 20% oil recovery. The non-selective treatment was then injected into the parallel stack system. The differential pressure was maintained at 10 psi/ft across the parallel stack configuration using a constant differential pressure pump. The selectivity of the treatment was approximately 70% for the high permeability stack. This is shown in figure 13.

Figure 13
Selectivity at 10 Psi/ft - Product #1



Once the treatment was injected, it was allowed to set followed by a post-treatment water flood. At 10 psi/ft there was a no-flow condition as shown in figure 14. As the pressure was increased to 20 psi/ft the previously-bypassed oil was then mobilized. The resulting oil recovery then allowed the low-permeability core to exhibit the same level of recovery as the higher-permeability core stack; conformance was improved.

Figure 14
REGAIN PERFORMANCE AFTER TREATMENT



Figures 15 and 16 show the change manifested by the implementation of the non-selective treatment at low differential pressure. Figure 15 shows the recovery performance before treatment and figure 16 the recovery after treatment but at 20 psi/ft instead of 10 psi/ft.

Figure 15
Oil Recovery on Parallel Waterflood

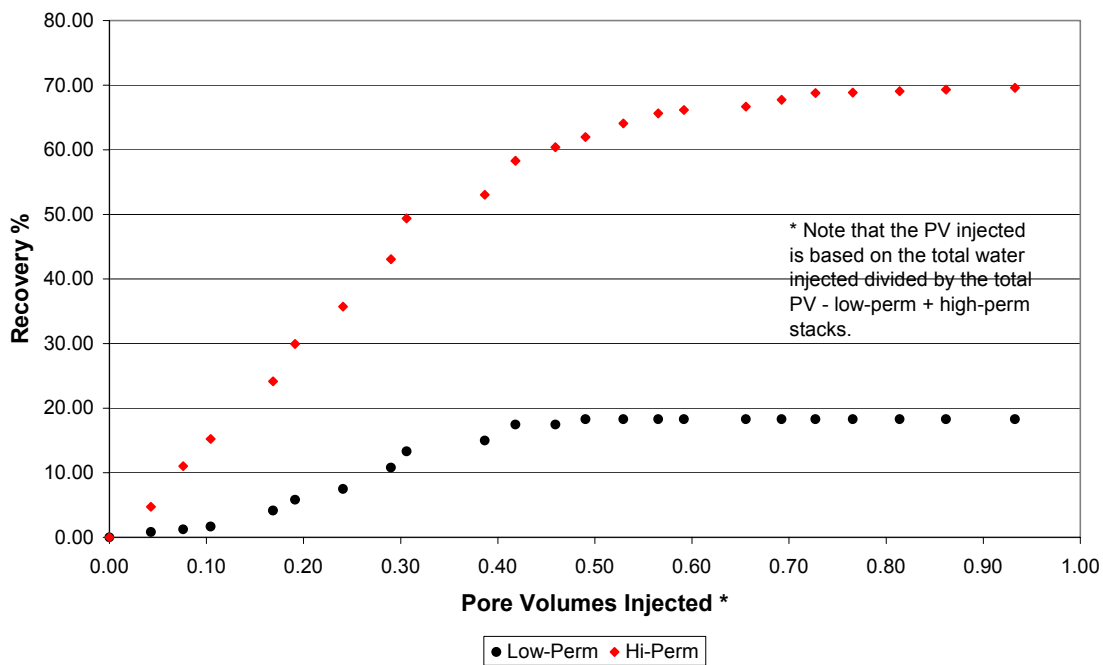
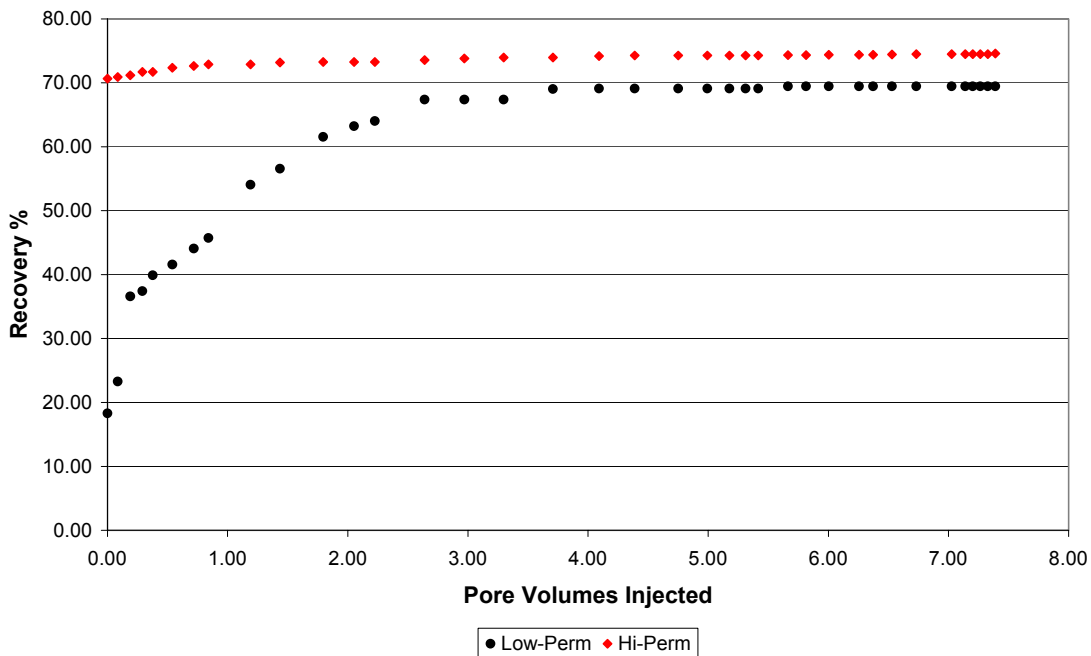


Figure 16
Oil Recovery to Waterflood after Diversion Treatment

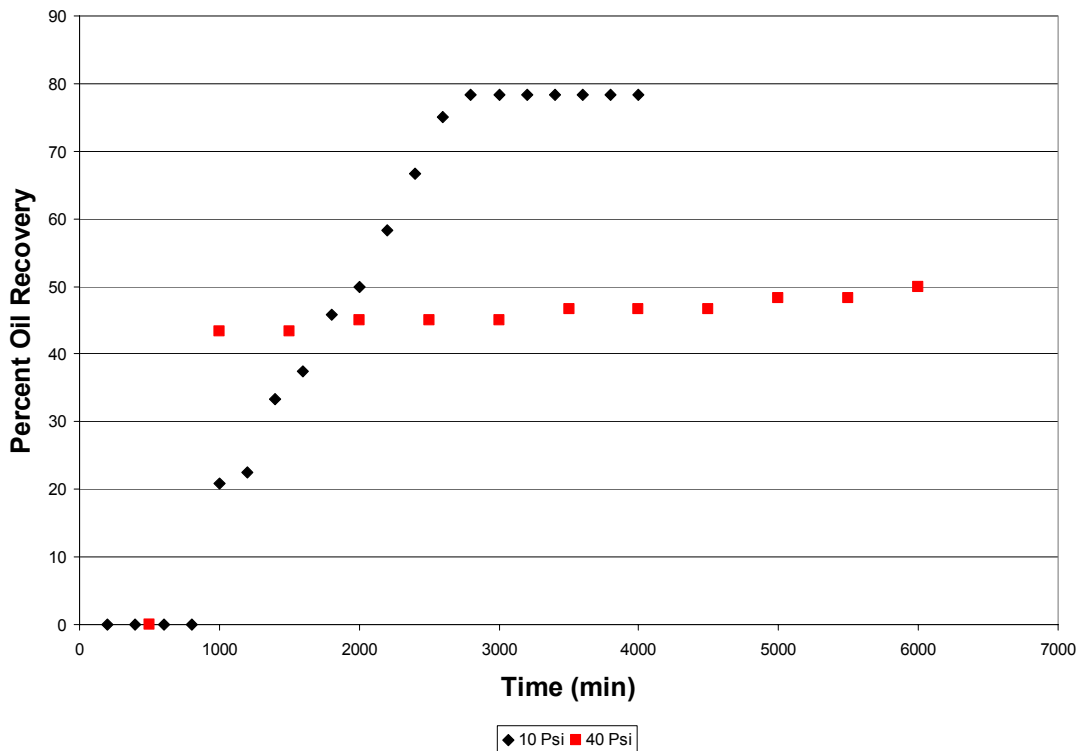


The reason for which the high-permeability stack exhibited very little incremental oil recovery was possibly due to the fact that the IFT limit may have already been reached.

Figure 17 shows a comparison of the performance of a similar set of core stacks, in parallel, with ultimate recovery after treatment and subsequent water flood. The recovery is significantly reduced by increasing the differential pressure at which the treatment was applied since the selectivity of the treatment was degraded - more treatment went into the low permeability core since at higher differential pressures threshold capillary pressure was exceeded during the treatment and the treatment was less piston-like in the already-flooded zones of the higher permeability stack.

Figure 17

Oil Recoveries on Regain



Conclusions

1. Two water shut-off chemistries were compared through linear core testing. The relative permeability modifier was not as effective in shutting off water as was the more aggressive blocking resin.
2. The water residual resistance factor was better for Direxit than for the RPM. The oil residual resistance factor was better for the RPM than for the oil. Reasons for this are detailed in the report and are considered to be due to the fact that the conduits for flow, water and oil, were relatively unchanged by the RPM whereas for Direxit it effectively changed the effective permeability of the total porous media.
3. Incremental oil recoveries after water flood were very comparable between the RPM but how the oil was recovered was very different. The RPM application recovered oil during the treatment whereas the Direxit application recovered oil after the treatment during the post-treatment water flood.
4. Treatments using non-selective chemicals are very sensitive to the differential pressure at which the application is placed. The lower the differential pressure the more IFT-dominated the treatments will be and the more efficient the conformance improvement. To increase the selectivity of field applications fluid-control equipment should be used.