SPE 99929

Should "Proactive" or "Reactive" Control Be Chosen for Intelligent Well Management?

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This paper was prepared for presentation at the 2006 SPE Intelligent Energy Conference and Exhibition held in Amsterdam, The Netherlands, 11–13 April 2006.

Abstract

Intelligent Well (IW) Technology combines zonal production control using Interval Control Valves (ICVs) together with installation of appropriate flow monitoring devices to improve well and field performance management. Zonal flow control can maximise produced oil value, minimise unwanted fluids or a combination of both objectives.

We have previously shown[1] that a minimum degree of un-evenness of an invading fluid front is needed for effective ICV control. This work studies scenarios to identify when "Proactive" rather than "Reactive" ICV choking policy can add greater value. Reservoir scenarios were created in which inter-zone connection, permeability contrast between zones, zonal length and other reservoir parameters were systematically varied. The interaction between the aquifer and reservoir was observed when producing these reservoirs with a horizontal IW using a range of "Reactive" and "Proactive" choking policies.

An example of successful "Proactive Control" is when the wellbore is intersected by a high-permeability channel. Here, early water or gas breakthrough leads to unwanted fluid being produced along with reduced volume of oil. Too early choking (or being "too Proactive") can result in losing oil as the "Good Water" is also blocked. "Proactive Control" will also be successful when reduced water or gas inflow is required due to tubing or surface handling limitations.

The key factor in successful Single Well "Proactive Control" is that other zone(s) can compensate for the loss of fluid from the choked zone(s). Its value thus increases when Artificial Lift is installed.

The value of "Proactive Control" is well known in multiple well scenarios. Here, value creation requires even-flood front management of an injected fluid at the field level. There is also the opportunity for other wells to supply extra oil production capacity when a (single) well is choked.

The results from this study can be used to screen for scenarios suitable for "Proactive Control", increasing the range of Intelligent Well Technology applications.

1. Introduction

The Intelligent Well system Technology (IWsT) has developed out of a need to improve reservoir and remote well management. Multi-zone, intelligent-well completions contain appropriate monitoring devices located between zonal isolation packers. They control the flow into or out of each zone with Interval Control Valves (ICVs).

Managing the future reservoir performance based on correct decision taking requires a model that accurately reflects the behavior of the reservoir system. Common reservoir management objectives are to reduce risk, increase production and reserves, maximise recovery and minimise capital and operating costs. IWsT has been shown to be capable of managing geological uncertainty[1]. Operating at or near real-time allows operators to fine-tune the performance of the whole production system by reconfiguring the well's completion system. The ultimate goal for this continuous monitoring of the reservoir is to implement a proactive reservoir management technique.[2]

The "Added Value" from an Intelligent Well depends on the optimum implementation of well control. It is best applied in a suitable reservoir[1] with an appropriate measurement and control system for the ICVs included as part of the well's completion. In this paper we will examine the impact of two, different, IWsT well management policies on the reservoir performance. This study will help determine which technique should be chosen when specifying the requirements for an effective, Intelligent Well management system.

The objective of zonal flow control using ICVs is to maximise the oil production and/or NPV, minimise the unwanted fluid productions or a combination of these objectives. ICVs are normally activated on the basis of the breakthrough time of unwanted fluids (water or gas). The activation policy can be either "Reactive" or "Proactive". We define "Proactive Control" as the choking of ICV(s) <u>before</u> water or gas breakthrough is observed at the well. "Reactive Control" is choking the ICV(s) after water or gas breakthrough has occurred at the well level.

We have already shown the application and performance of “Reactive ICV Control” in a wide range of generic and real reservoir types.[1, 3, 4] Brouwer et al.[5] presented a study in which the optimisation technique focused on reducing the difference in time of flight from the injector to producer in a water flood environment. Their method involved manipulating the well segments’ productivity index (PI) to maximise total well production. Yeten et al.[6] presented a general method for the optimisation of a well equipped with ICVs. Their method entails the use of an optimisation tool based on a conjugate gradient algorithm. This optimisation tool was linked to a commercial reservoir simulator containing a wellbore flow model capable of modeling ICVs. Their optimisation approach required that the simulation be divided into a number of optimisation steps. The valve settings were optimised for each time period. Their method was applied to examples involving vertical wells in a layer-cake reservoir and multilateral wells in a complex channelised reservoir. It proved possible to improve cumulative oil recovery using a defensive (“Proactive") control methodology. Aitokhuehi et al.[7] combined IW optimisation on the basis of Yeten et al.’s work and history matching techniques. Use of multiple history matched models provided improved results in some cases. In this work we will compare the effectiveness of the “Proactive” and “Reactive” ICV Control.

2. Potential Value of “Proactive” Control

“Proactive” reservoir management can add value by optimising reservoir performance at the “Field Level” by developing an even flood-front along the length of the wells in the reservoir. In this work we will evaluate the effectiveness of “Proactive Control” on a “Single Well Basis” rather than the “Field Level”. “Proactive reservoir management Control” requires a greater knowledge of the reservoir than that required for “Reactive Control”. This arises from the need to optimally control the distance of the water or gas flood front from the wellbore as a function of time and fraction of the original oil-in-place recovered within the well’s drainage area.

3. Model Construction

Figure 1 shows a cross-sectional view of the basic reservoir model, used for creation of the scenarios to be studied. It is a 3D model with 3 distinct layers. It has 20 grid elements in X-direction, 50 elements in Y-direction and 116 elements in Z-direction (total 116000 grid cells). Each grid cell is dimensioned 50 x 50 x 1 m in the X, Y and Z directions respectively. Table 1 summarises the porosity and permeability values used.

The “Added Value” for an Intelligent Well has been shown to be a function of the un-evenness of the movement of the fluid-front towards the wellbore.[1] Many parameters affect the fluid front’s movement – the fluid properties, relative permeabilities among others are of great importance. In this study the relative permeability and capillary pressure curves were calculated as a function of the absolute permeability based on Pickup, G., et al’s work.[8]

Figure 2 exemplifies the well-known importance of the relative permeability curves on the shape (un-evenness) of the flood-front as it moves towards the wellbore. It thus impacts the “Added Value” from Intelligent Wells[1]. Figure 2 shows the effect of replacing the relative permeability curve for the low permeability layer with one more appropriate to a high permeability zone. A 5% increase in the oil recovery for the “no ICV” case is recorded since the un-evenness shown by the flood-front as it moved towards the wellbore was reduced. Hence the opportunities for flow control, and hence the “Added Value” for IWsT, was also reduced by the use of inappropriate relative permeability curve for the low permeability layer (Faster production from the low permeability layer has resulted in this case).

Inappropriate relative permeability curves can increase or decrease the “Added Value” for Intelligent Wells; depending on how they affect the shape of the flood-front as it moves towards the wellbore. It is also a function of the number and the position of the ICVs along the length of the wellbore.

The generic geological model used for this study (Figure 1) is based on a sequence of sandstone deposition events in a deep-water, marine environment with interbedded sand, silt and mud. These sediments could have been deposited in highly turbulent sediment flow from the sediment source. The sand bodies consist of two distinct layers – a high permeability sandstone with a permeability of 1000 mD and a low permeability sands of 5 mD permeability. The stratigraphic trap was formed from the deposited shale and mudstone layers (0.1 mD), the latter being formed during periods of low energy flow. Continued sediments transport, bedform migration and sediment deposition leads to the development of this type of sedimentary structure.[9] The 1.5 degree inclination shown in Figure 1 could have been formed by a salt dome pushing upwards or by fault slides creating either reverse or normal faults.

4. Study Methodology

A range of reservoir situations were created to perform a systematic study of the interaction between the:

i. Aquifer and reservoir
ii. Degree of connection between the zones which are being controlled by the ICVs
iii. Permeability contrast between the zones
iv. Length of the zones being controlled by the ICV
v. Reservoir and aquifer pressure and other reservoir parameters
vi. The reservoir models were chosen so that the degree of un-even fluid front needed for effective control could be observed.

Manual optimisation techniques[1, 3, 4] for reactive and proactive control, as provided by the Eclipse simulator package capabilities[10], have been applied for the control of the ICVs. The ACTION keyword was used to specify a field condition (e.g. a water cut limit) for triggering an action. The action is carried out by a specific well segment, which in our case represents a valve in the segmented well. The WSEGVALV keyword designates the appropriate segment within the well. The flow-regime in the valve is sub-critical, hence an additional pressure drop in the segment due to flow is imposed when the ICV action is triggered. The valve constriction has a specified cross-sectional area (Ac). The optimisation parameters used during the well's production life were the number of ICVs, the ICV flow diameter, choking time and the choking policy ("Reactive" or "Proactive" Control).

The reservoir scenarios were deliberately kept relatively simple so as to:

1. Help comparison between cases and
2. Allow a better understanding of the role of the "Reactive" versus "Proactive" control on any changes in the "Added Value" from an Intelligent Well.

In all cases performance of the well with both of these IWsT modes was compared with production from an equivalent well with the ICV permanently in the fully open position (the base case). The well flow rate was controlled at a target liquid rate of 2,000 m^3/day. Table 2 shows the range for each sensitivity parameter studied.

Previous work with this type of model confirmed that, as expected, choking of the high permeability zone encourages greater production from low permeability layers. This occurs because the well's production was not outflow limited; being controlled by the total liquid rate. This can result in delayed water breakthrough at the well level, allowing better sweep efficiency in the low permeability zone. Figure 3 shows the presence of trapped oil in the reservoir when producing it with a conventional well.

ICV1 was placed across the complete high-permeability layer. The well (or zone) length it controls was kept constant for all sensitivities studied. The model was modified during the latter parts of the study (Figure 9 and Figure 12). A second ICV (ICV2) was also introduced to control the water break-through at the very end of the well (Figure 12). The well (or zone) length controlled by ICV2 was kept constant for all scenarios.

4.1. Choking Policies

The choking policies for Reactive Control allowed changing the water cut at which choke action was triggered. We have examined different choking policies:

i. *Single choke action*. Here the choke size stayed constant for the remainder of the well's life after the single choking event.
ii. *Two control actions optimally spaced*. The choke size was reduced to a certain diameter initially and then made reduced again later in the well's life when the water cut became too high.

A wide range of sensitivities were performed to identify the optimum values for ICV size and triggering time within the above policies.

Similar choking policies have been studied for "Proactive Control".

i. *Single control action* for the ICV so that choking took place some time before the water broke-through into the well.
ii. *Two control actions*, one was set before water breakthrough ("Proactive") while the second one was "Reactive" with choking later in the field life to curb an excessive water cut.
iii. *Three control actions*, one control action was "Proactive", occurring before the water breakthrough time, while the final two took place later on ("Reactive").

The flexibility in manual optimisation was increased systematically during the study to allow development of a better understanding of the performance of "Proactive" control on a "Single Well" Basis.

5. Results and Analysis

Figure 4 is an overview of the models studied and the simulations performed.

5.1. The Original Model

Figure 5 compares the performance of "Proactive" and "Reactive" Control with the base case. "Proactive Control" accelerated the production and increased recovery by 6.2 %. This was slightly (0.3%) better than when a "Reactive Control" policy was employed.

Optimum "Proactive" Control required choking of the ICV 175 days before water breakthrough occurred at the well. "Proactive Control" increased production from the low permeability layer to such an extent that plateau period was extended when a comparison is made with the base case. This was due to extra production from the low permeability zone which now experiences a later water break-through during the field life. This is shown in Figure 6, which depicts the oil flow rate at the ICV controlling the flow from the high permeability layer. The well was able to continue producing at the plateau rate for a longer period than for the base case. This was achieved despite choking the high permeability zone that had previously been producing 85% of the well's production. The net result was an improved recovery from the reservoir.

Figure 7 illustrates the significant (40%) reduction in water production compared to the base case. "Proactive Control" will normally delay water breakthrough and reduce the cumulative water production compared to the "Reactive Control". (Remember, the ICV is a choke!). The magnitude of the difference in recovery between these policies will depend on the particular choking policy chosen and the case being studied.
N.B. Both "Reactive" and "Proactive" Control can be highly successful when reduced water or gas inflow is required due to tubing or surface handling limitations. "Proactive Control" will be preferred under some scenarios as it both reduces and delays the total volume of unwanted fluid produced.

Figure 8 compares the performance of both “Proactive” and “Reactive” control for a wide range of choke trigger times and Reservoir Pressures. It illustrates how choking too early, or being “too-Proactive”, will result in a loss of oil. The optimum choke triggering time for “Proactive Control” in this study is between 100 to 200 days before water breakthrough for a reservoir pressure of 370 bars. The optimum severity of the choking to be applied will vary with the time (before water-breakthrough) that the choke action is triggered. Choking later implies that a slightly more severe (reduced diameter) choke is required for optimum performance. However, in this example the difference is small and the “Added Value” of “Proactive” compared to “Reactive” control remained approximately constant.

The amount of choking, or the internal diameter of the ICV, was kept constant at each of the trigger times shown in Figure 8. This was done to aid comparison of the results However, a wide range of sensitivities were performed on the choking severity for each of the trigger times illustrated in Figure 8.

Figure 8 also illustrates the choke trigger times for different reservoir pressures supported by a constant aquifer pressure. It shows that lower reservoir pressures gave a higher value for IWsT. The greater pressure differential between the reservoir and the aquifer pressures implies that a greater pressure support is available. This creates an earlier, more un-even, fluid-front movement towards the wellbore. Hence, there will be more opportunities for flow-control and a higher resulting “Added Value” from IWsT.

The distance of the invading oil/water flood front from the wellbore was 10 meters in the above example of effective “Proactive Control” (ICV trigger time of 175 days before water-breakthrough). This distance is obviously an important criterion for deciding on the type of downhole sensors needed for effective recognition of invading fluid fronts. In this particular case a long-spaced resistivity array would be suitable for “Proactive” control. However, this distance is very case dependent, being a function of the layers permeability, permeability heterogeneity in the reservoir, volume of the oil reservoir and the aquifer, well length, the well drainage area, target production rate and many other parameters.

5.2. Modification of aquifer support by Partial Removal of the very Low Permeability Layer

Figure 9 shows the cross-section of the Figure 1 model which has been modified by partial removal of the very low permeability layer at the bottom right of the reservoir. This was done in order to modify the aquifer support to the layers by creating greater communication between the layers. Fluid front performance in Figure 10 illustrates how the aquifer water on the right-hand side of the model no longer supports the complete low-permeability zone. Water flow is concentrated in that part of the layer immediately above the region where the very low permeability layer has been removed.

Insufficient pressure support is now given to the low permeability layer. It is no longer able to compensate for the loss in fluid production from the high-permeability zone when the ICV controlling the high-permeability zone is triggered.
Figure 11 shows the performance of Proactive and Reactive Control compared to the base case. “Proactive Control” performed better than the “Reactive Control”, although the “Added Value” for IWsT was slightly less than the original model. The optimum ICV trigger time for Proactive Control was found to be 50 days before water breakthrough occurs. I.E. A smaller degree of Proactive Control was optimum. This occurs because the “Added Value” for IWsT is now limited to extra production from the low permeability zone, the full potential of which could not be exploited due to lack of aquifer support.

5.3. Addition of a Permeability Barrier to modify the Aquifer Support

Figure 12 shows modification of the aquifer support by addition of a permeability barrier. Figure 13 illustrates how the water flood is now restricted to the high permeability layer, resulting in the low permeability layer suffering a low sweep efficiency. A second ICV was introduced to control water production flow from the far right section of the model (ICV2 in Figure 12). “Reactive”, “Proactive” and “Mixed Mode” choking (a combination of both “Reactive” and “Proactive” control) were studied for both ICVs.

Figure 14 illustrates the case of ICV1 being controlled by a “Reactive” policy and ICV2 with a “Proactive” Policy. The performance is compared with the case of fully open ICVs. In this case the oil production was unaffected by the ICV control due to the limited aquifer support to the trapped oil in the low permeability layer. N.B. Increased production to compensate for the loss of produced oil when the ICV is triggered was required from this layer in the above scenarios. However, a slight improvement in recovery was observed compared to Figure 10.

Figure 14 records a substantial reduction in water production despite this lack of success in increasing oil production.

5.4. Artificial Lift Installation compensates for the lack of aquifer support

Figure 15 shows the performance of a well equipped with Artificial Lift (AL). The ICV choking action in the high permeability layer was triggered 270 days before water break-through. AL was applied at the same time as this “Proactive ICV choke Control” of the flow from high permeability layer. The AL improved the well inflow performance, encouraging extra production from the low permeability layer. An increased “Added Value” of 22 % extra recovery was achieved for “Proactive Control” compared to the “no ICV + no AL” case (Figure 15).

5.5. Reduced Target Liquid Rate

The lack of efficient aquifer support was identified as the main cause for the limited “Added Value” from ICV control in the above scenarios. The requirement for aquifer support was therefore reduced by lowering the well's target rate.

Figure 16 shows the performance of the well completed in the Figure 12 reservoir model after reduction of the target liquid rate from 2,000 m^3/day to 1,500 m^3/day. The low permeability layer is now able to compensate for the loss of oil production from the high permeability layer when its flow was reduced by "Proactive" Control of the ICV. (N.B. This compensation was not possible with a well target rate of 2,000 m^3/day). The "Added Value" for the reduced target rate coupled with "Proactive Control" was a 3.3% increase in recovery together with 34% reduction in water cut. This extra oil can be largely attributed to the reduced water production improving the tubing outflow performance, allowing the well to remain on production for a longer time.
N.B. This applied to a varying extent to the other scenarios as well.

5.6. Re-open the ICV Later in Field Life Improves Well Deliverability

Figure 17 shows the performance of the well for the reduced target rate of 1500 m^3/day. Both ICVs were re-opened later in the field life. This scenario was chosen to illustrate that very significant volumes of unswept oil remained in the model that could be recovered by a more complex choking policy in the mature phase of the well life.

Increased oil production (rather than reduced water production) can thus only be achieved when excess well deliverability exists.

6. Conclusions

The key learning from this study with the objective to identify successful Single Well "Proactive Control" scenarios is that:

1. Alternative production zone(s) must be able to compensate for the loss of fluid from the choked zone(s). Knowledge of the parameters effecting the movement of the fluid-front (e.g. permeability distribution, strength of the aquifer support at all points within the model etc.) is required when preparing an "Added-Value Statement" for IWsT.

2. Too early choking (being "Too Proactive") can result in losing oil as "Good Water" is also blocked.

3. Added value increases when well target rate is reduced or Artificial Lift installed. This allows alternative zones to compensate for the loss of fluid from the choked zone(s).

4. Both "Reactive" and "Proactive" Control is highly successful when reduced water or gas inflow is required due to tubing outflow performance or surface handling limitations. "Proactive Control" will be preferred under some scenarios as it both reduces and delays the total volume of unwanted fluid produced.

Acknowledgements

The authors wish to thank Muhammad Maulut for his contribution towards the project, Geoquest & Roxar for software provision and the "Added Value from Intelligent Well systems Technology" JIP project sponsors in Heriot-Watt University (BP, BG, ENI, Statoil, Norsk Hydro & WellDynamics) for providing financial support.

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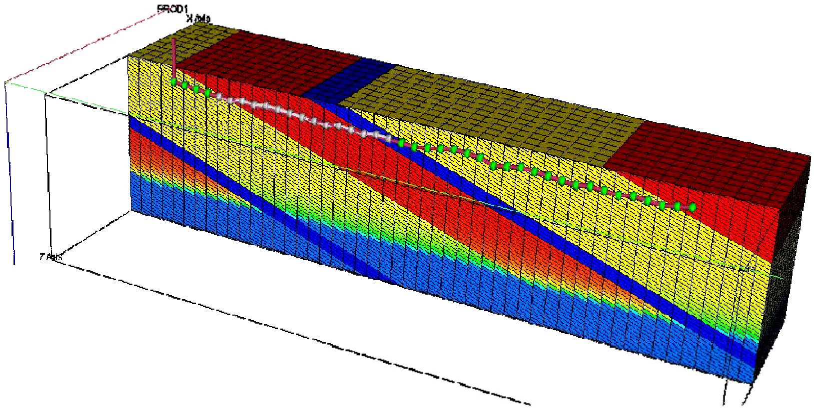

Figure 1: A Schematic of the Reservoir Model

Layer	Permeability (X & Y directions) md	Permeability (Z direction) md	Porosity (Fraction)
High Permeability	1000 mD	500 mD	0.23
Low Permeability	5 mD	2.5 mD	0.20
Very Low Permeability (Shale)	0.1 mD	0.05 mD	0.1

Table 1: Permeability/Porosity for the reservoir model

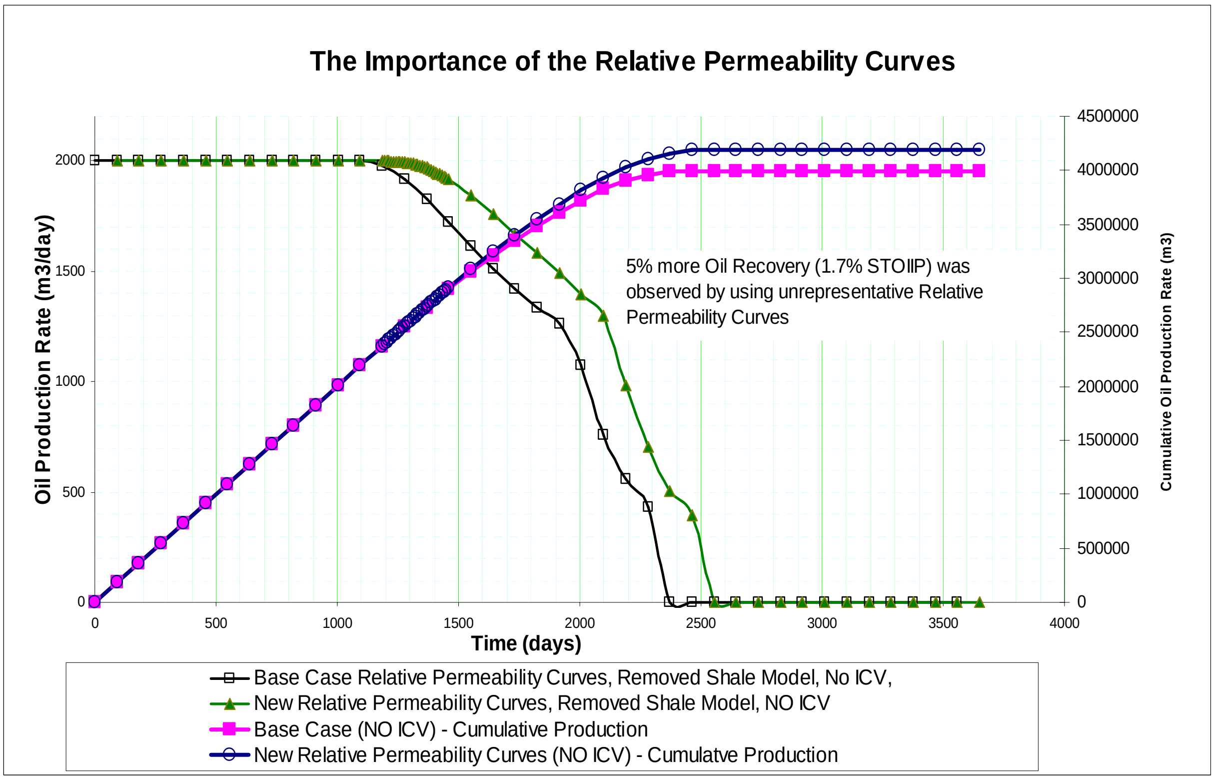

Figure 2: The Importance of Relative Permeability Curves

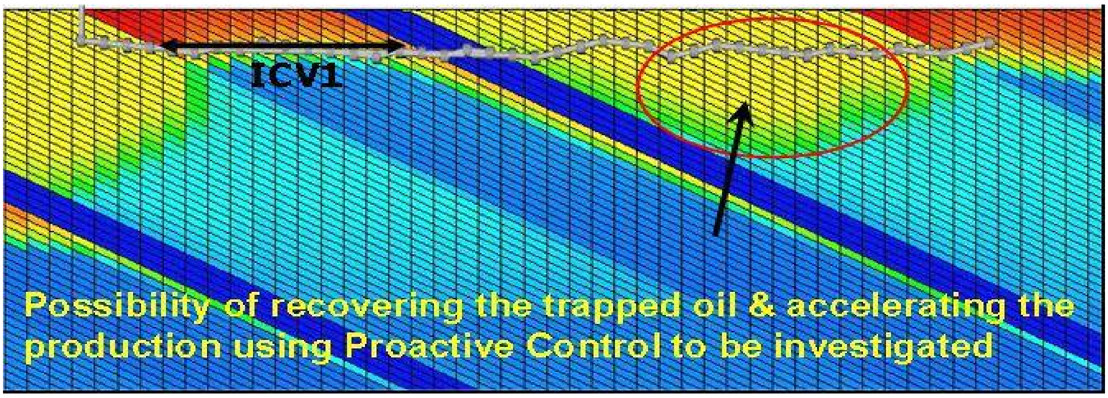

Figure 3: A slice of the model showing trapped oil by producing the reservoir with a conventional well

Sensitivities	Minimum	Maximum
Water Cut at which the ICV triggered (Reactive Control)	1%	30%
ICV Choke Size	0.000025 m2 (0.2 inch ID)	0.001 m2 (1.4 inch ID)
Reservoir Pressure	370 bars	500 bars
Choking Time for Proactive Control (Days before water breaks through)	9 days	821 days

Table 2: The range of sensitivities performed

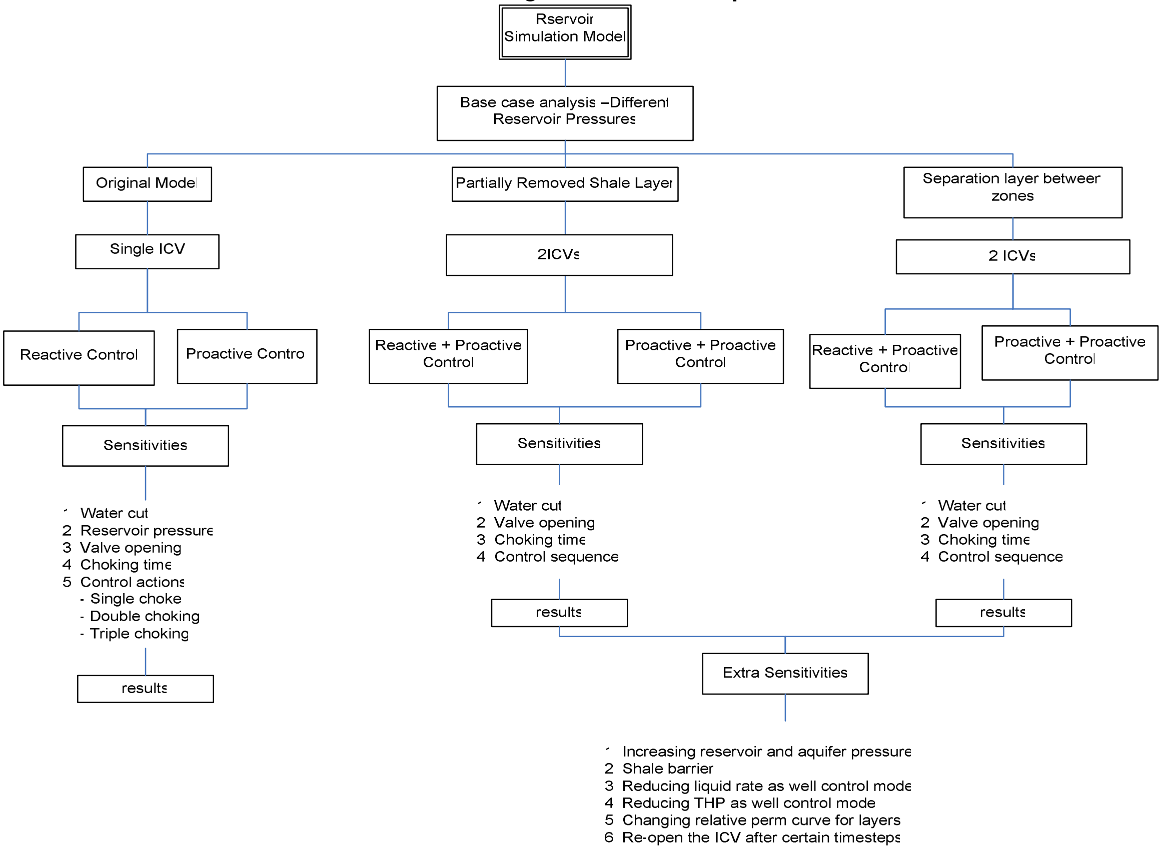

Figure 4: An overview of the simulations and sensitivities performed

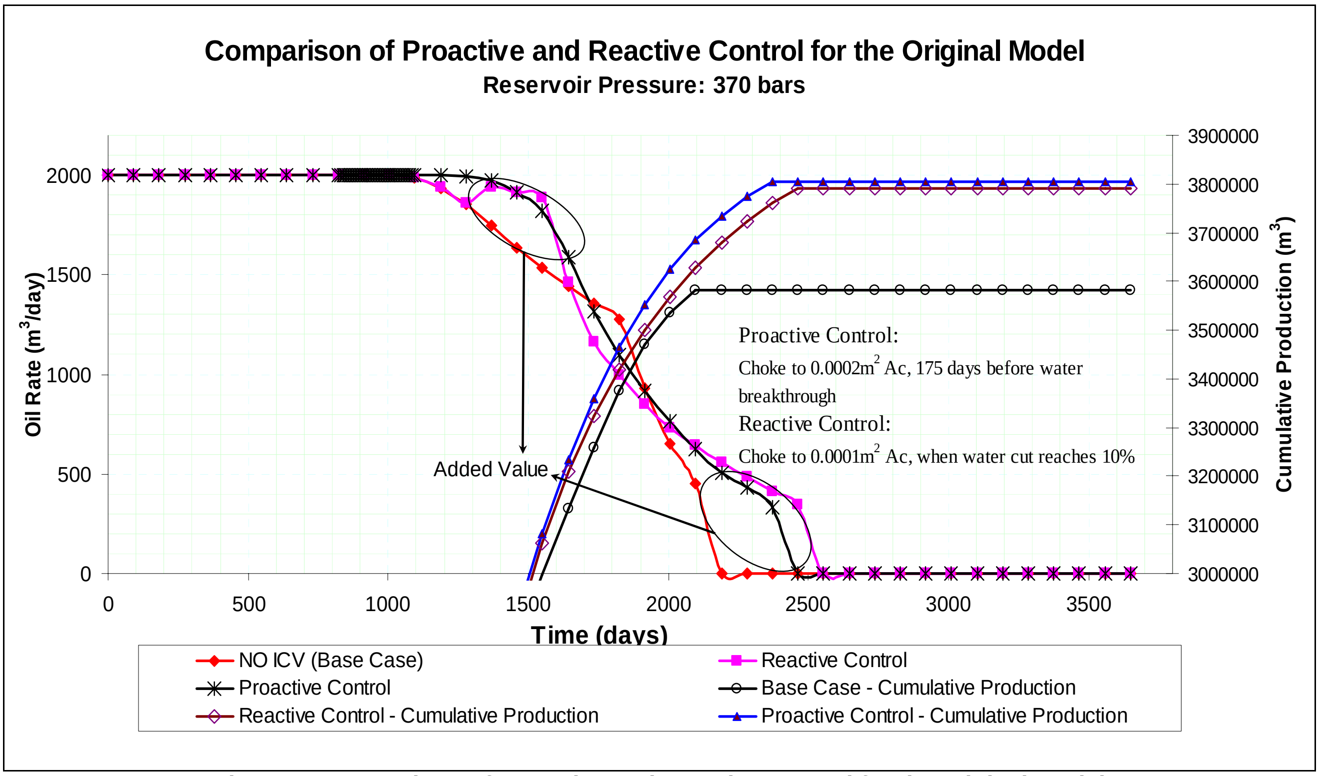

Figure 5: Comparison of Proactive and Reactive Control for the original model

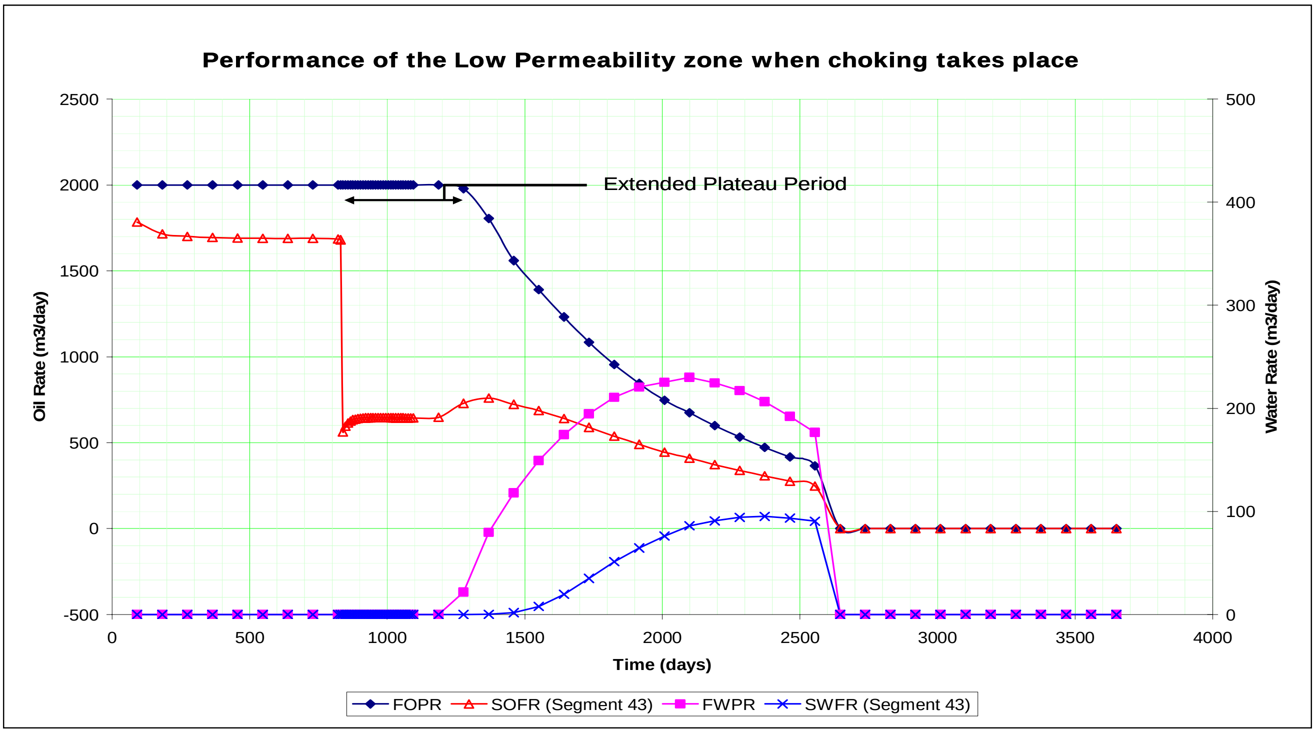

Figure 6: Increased Oil Production from Low Permeability Zone due to "Proactive" ICV Choking

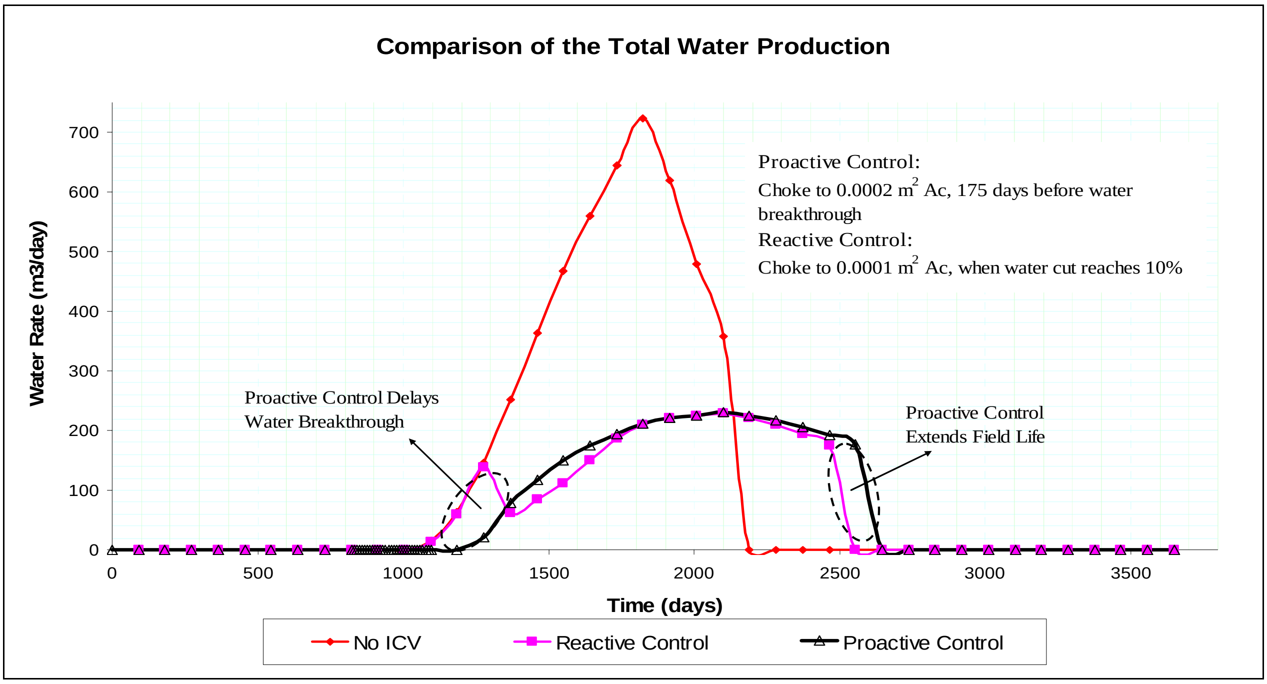

Figure 7: Comparison of the Total Water Production for the original model

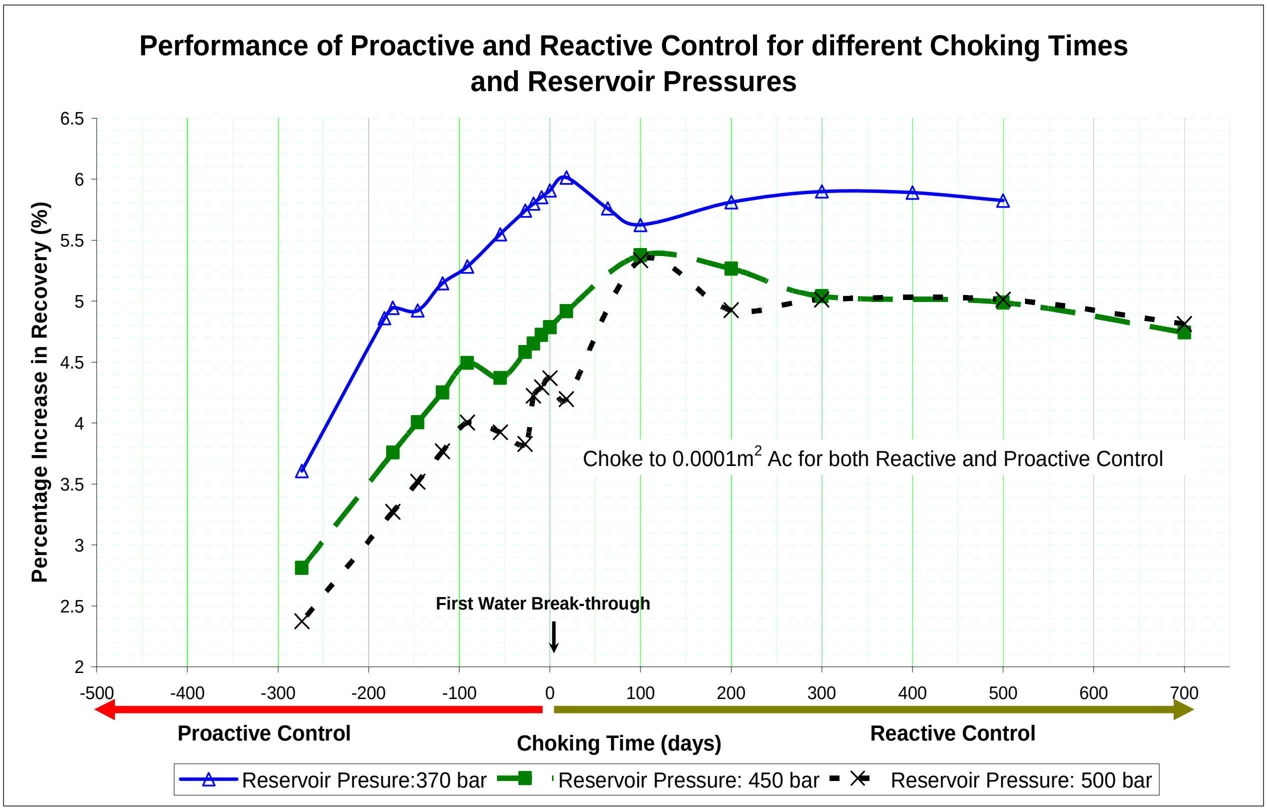

Figure 8: Performance of Proactive and Reactive Control for different choking times and reservoir pressures

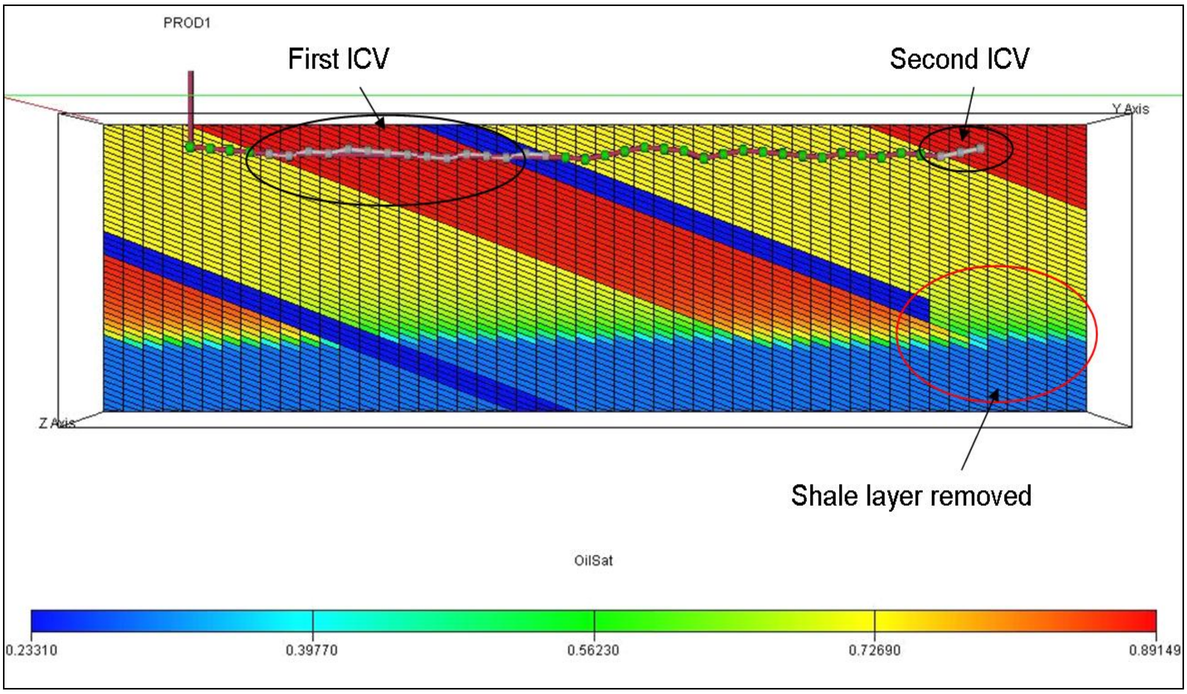

Figure 9: Partial removal of shale barrier creates communication between the compartments

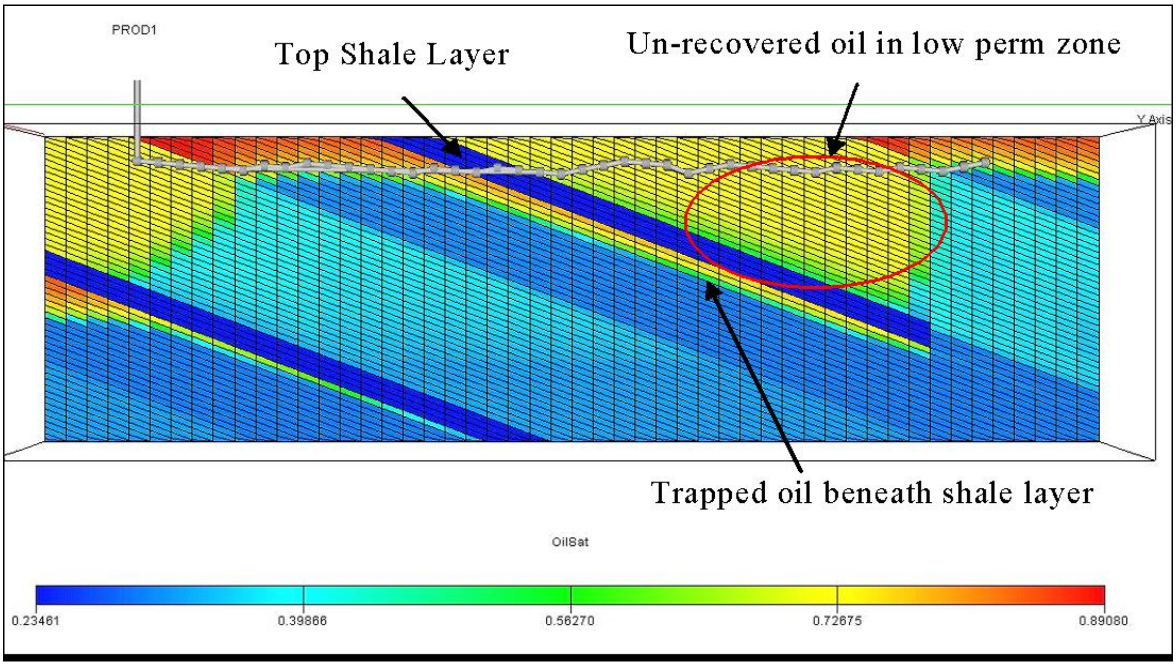

Figure 10: Communication between compartments reduces sweep efficiency

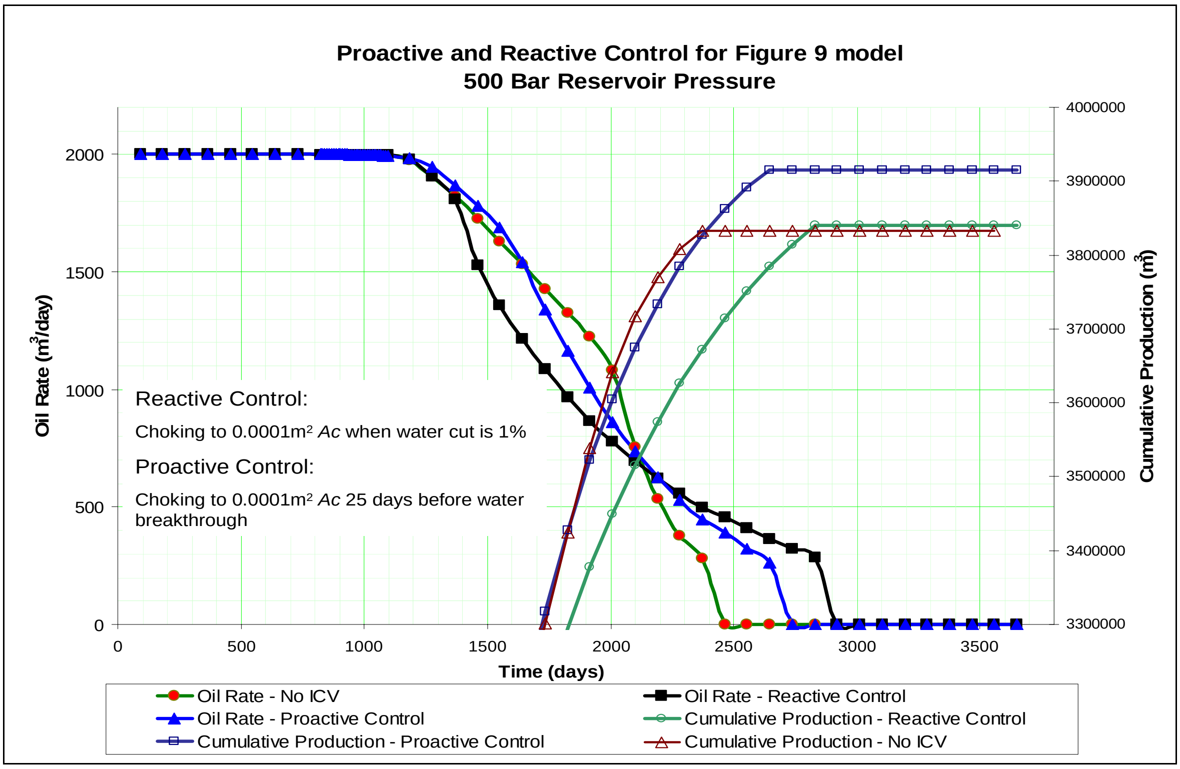

Figure 11: Comparison of Reactive and Proactive Control for the Figure 9 model

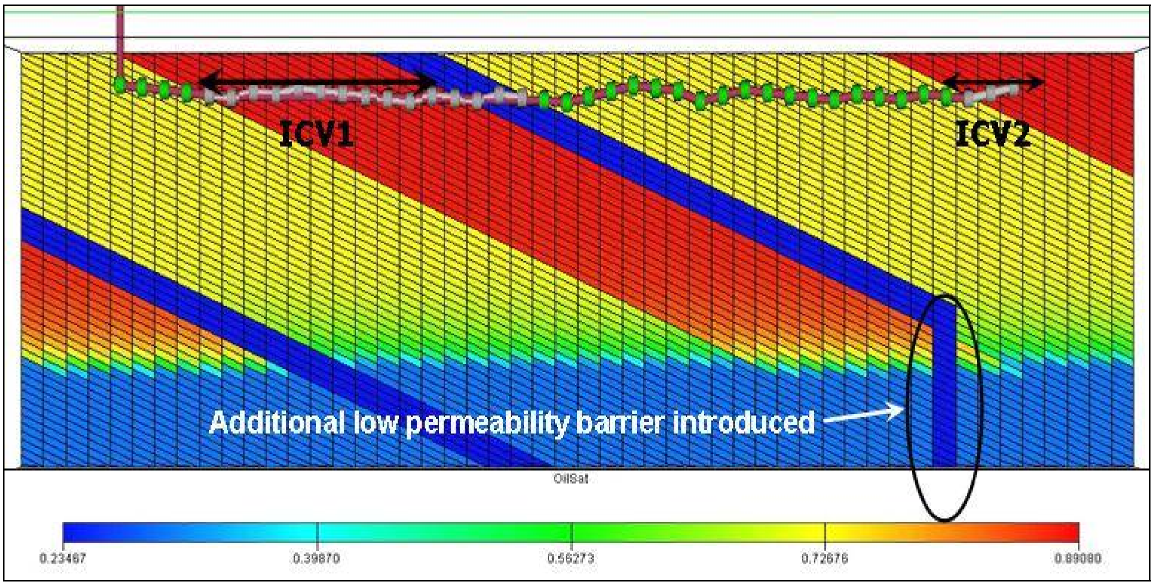

Figure 12 : Additional low permeability barrier modifies the aquifer support

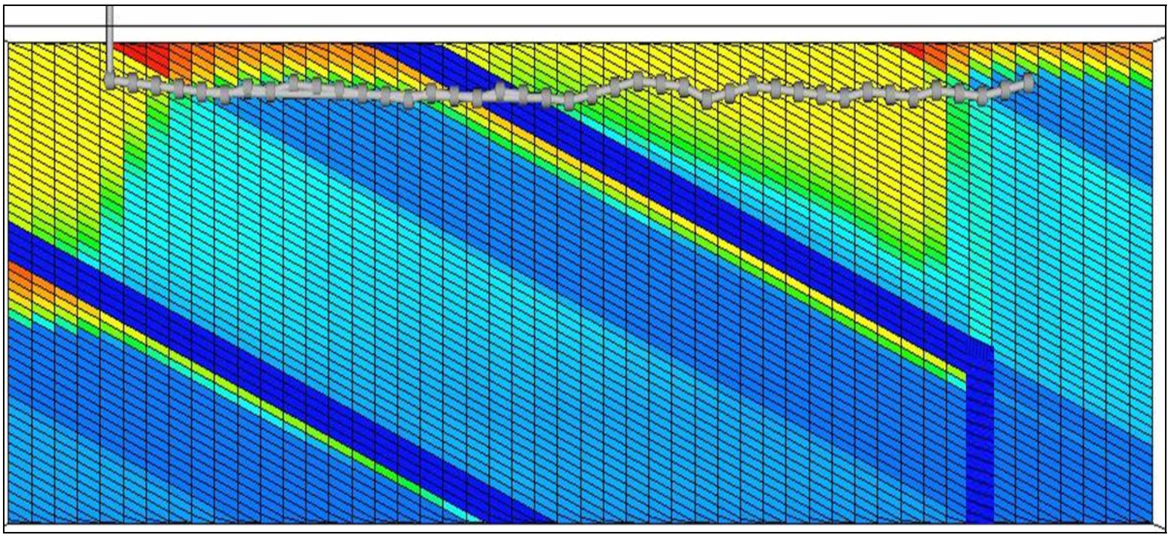

Figure 13: Only a slight increase in the sweep efficiency is observed compared to Figure 10

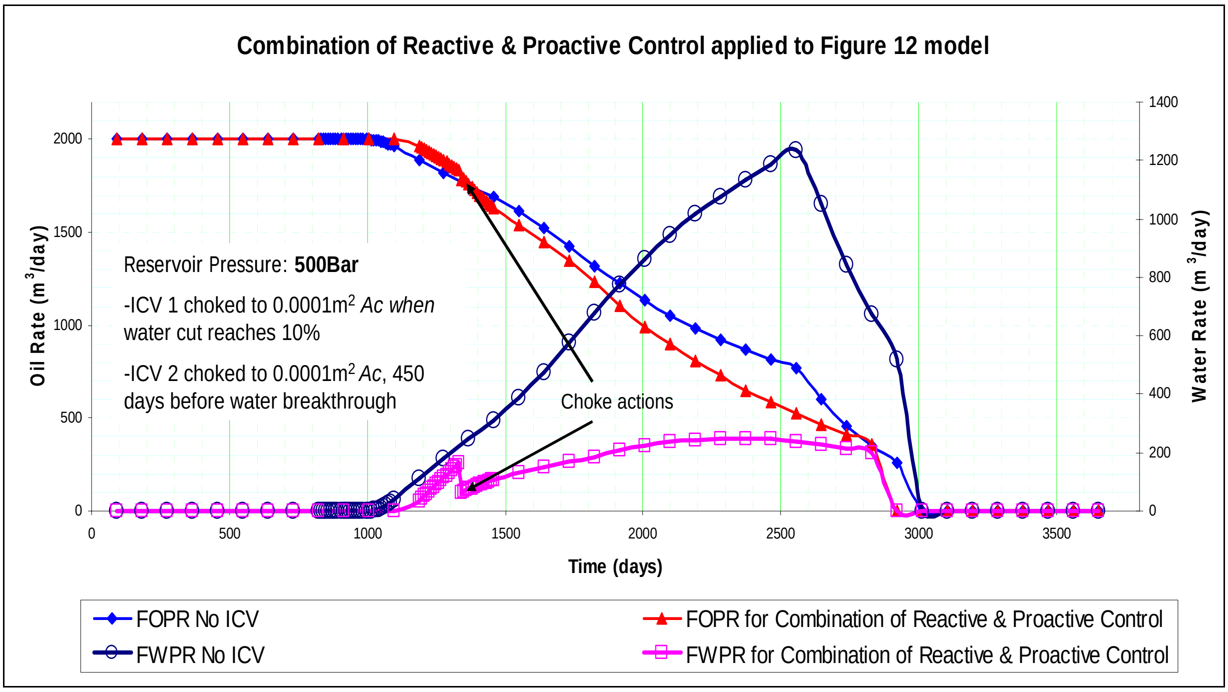

Figure 14: Comparison of Reactive and Proactive Control for the modified model 2

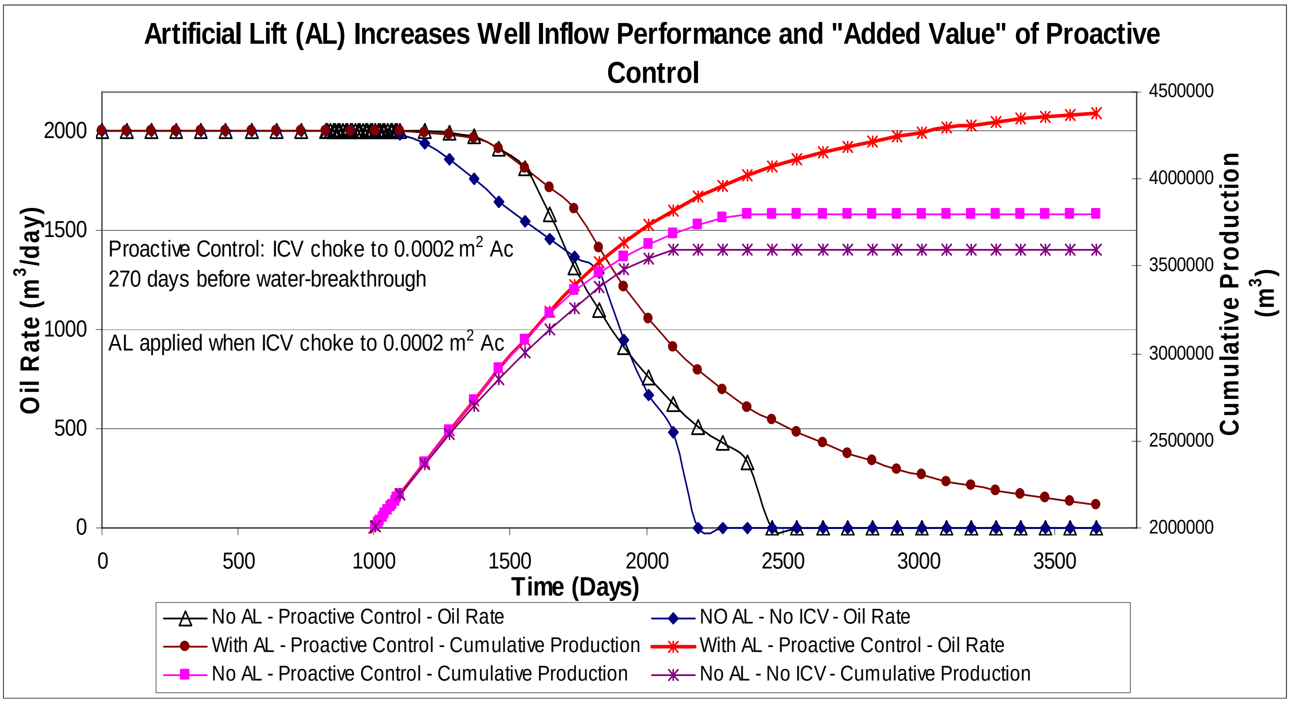

Figure 15: Application of Artificial Lift with Proactive Control

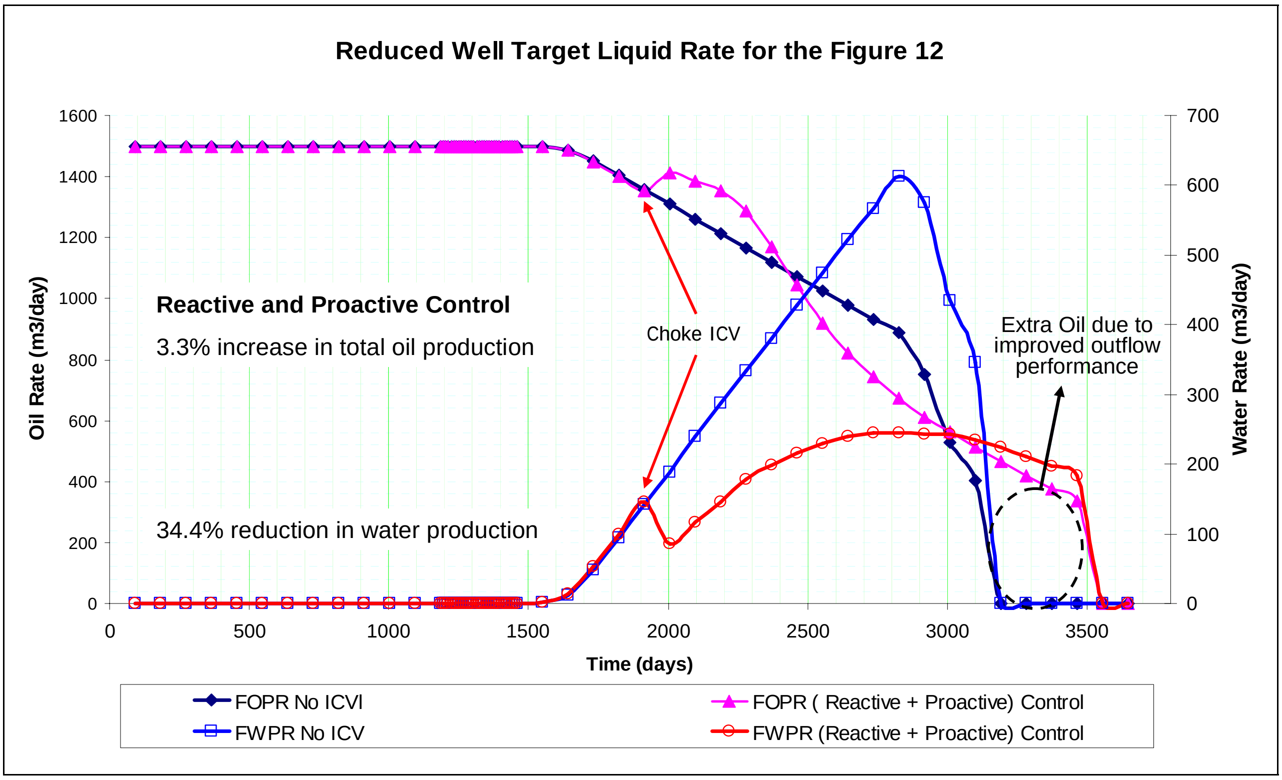

Figure 16: Reduced Well Target liquid rate for the Figure 12

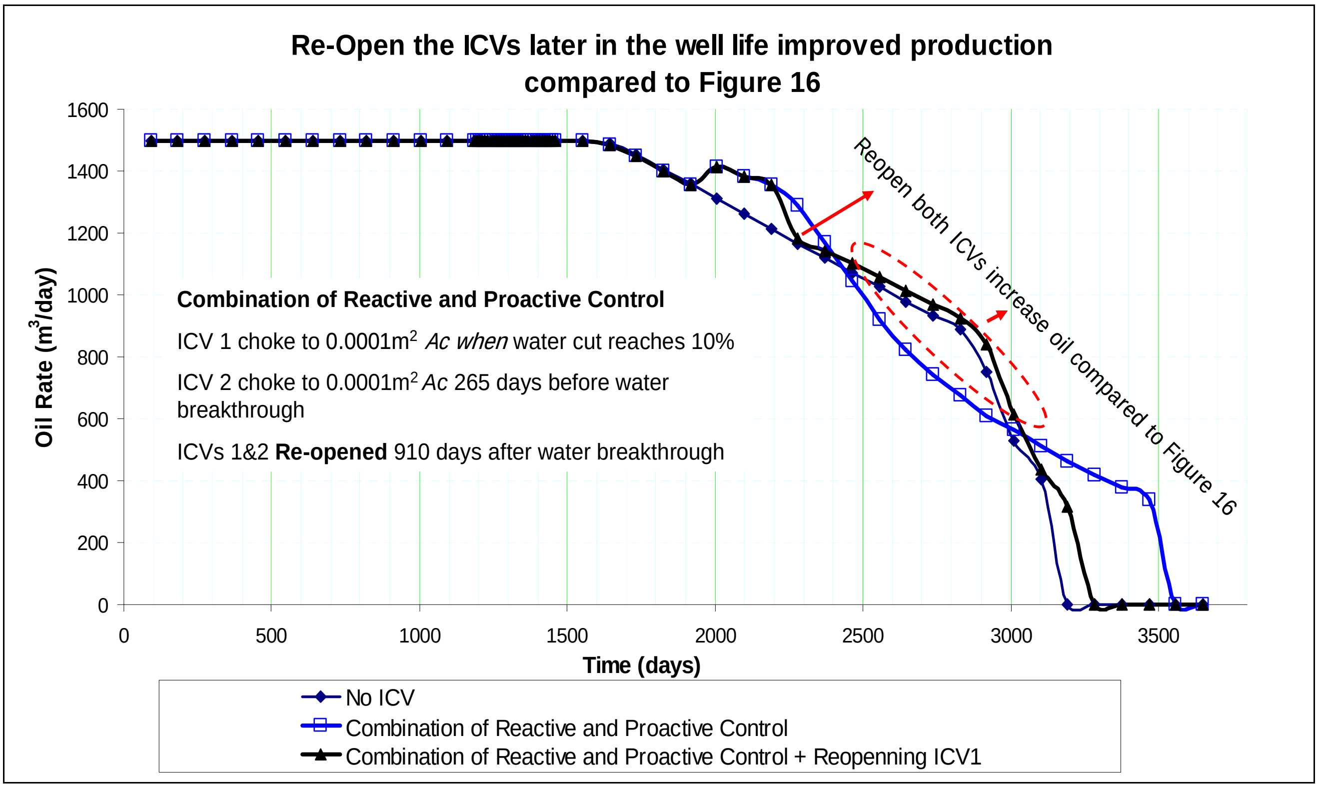

Figure 17: Re-opening the ICV later in the well life improved production