Abstract
Multilateral-well technology improves well productivity by maximizing reservoir contact, resulting in field development with fewer wells and minimizing water and gas coning. The current practice of drilling long horizontal wells (up to eight km) poses the greatest technological challenge in completing the wells because of geological uncertainties, hydraulic and mechanical complications. Tremendous efforts have been made by the oil industry to meet these drilling challenges, and also in the design and completion of these types of wells. Since 2002, over 440 horizontal, multilateral and maximum reservoir contact (MRC) wells have been drilled and equipped with active Inflow Control Valves (ICV) and passive Inflow Control Devices (ICD) in Saudi Aramco. The complex architecture of those wells generally makes them more expensive to drill and complete. Therefore, their use must be justified and well planned. The planning of complex architecture wells requires thorough modeling studies to optimize total length, configure branches, place ICV and ICD along the motherbore to achieve balanced inflow along the laterals, overcome high frictional pressure loss from heel to toe, alleviate reservoir pressure variation along the laterals, decrease coning or cusping of gas and water, and control gas or water production from offending laterals.

Advanced well completion technology, which improves well productivity and maximizes sweep, is becoming the main stream development technology in Saudi Aramco. Numerous future wells and reentries are planned as complex architecture wells with smart completions. Realizing the important role of reservoir simulation, and the difficulties of modeling and optimizing of these complex architecture wells, Saudi Aramco embarked, in 2002, to develop simulation technologies for the evolving complex architecture wells with smart completions.

In-house simulation and optimization efforts for complex architecture wells with smart completions have increased drastically since 2002. In fact, two industry joint projects, with a service provider, developed a new simulation workflow for the complex architecture wells with smart well completions. This paper will present simulation, design and optimization of four field cases with complex architecture wells equipped with ICD and ICV. Well configurations, geologic uncertainty and placements of ICD and ICV along the laterals are optimized using the neural network, genetic algorithms, and proxy models.

Introduction
Worldwide drilling of horizontal wells increased in the mid-1980. Beliveau (Beliveau 1995) compared production performance of horizontal wells with offsetting vertical wells. He calculated the production improvement factor (PIF) for 1306 horizontal wells from 230 fields around the world. The calculated PIF’s showed log-normal distribution caused by geologic heterogeneities compounded by mechanical drilling and completion effects. The results revealed a mode PIF of 2, a median PIF of 3, and a mean PIF of 4. One benefit of horizontal wells is that they can seek out more sweet spots (more permeable area or zone) by drilling through or contacting more reservoir rock. Many other factors such as length of the horizontal laterals, wellbore configuration, formation damage (skin), reservoir pressure profiles, unexpected fractures, and baffles affect the rate distribution along the horizontal wellbore.
Brekke and Lien were the first to propose simple alterations to the completion that could enhance the performance of long horizontal wells produced from heterogeneous reservoirs having high-permeability streaks (Brekke and Lien, 1994). They based their invention upon the fact that the frictional pressure loss along the horizontal well can restrict the inflow from the reservoir to a horizontal well in high-permeability formations. In a horizontal well, the heel contains the highest drawdown pressure and, consequently, the highest influx flow profile. The area close to the toe contributes less to the production than the heel area. Brekke and Lien optimized the completion design based on three basic principles: (1) reduction of the frictional pressure loss along the perforated part of the horizontal, (2) redistribution of the frictional pressure loss along the perforated part of the well by changing the flow direction in parts of the liner, and (3) creation of an optimal sandface pressure profile by introducing inflow control along the horizontal wellbore.

Evolution of Complex Architecture Wells with Smart Completion in Saudi Aramco

Horizontal drilling intensified in the late 1990s with the Shaybah Field development in Saudi Aramco. Shaybah Field was developed in 1996-1998 with 1-km single lateral horizontal wells to drain the hydrocarbon while reducing gas coning. From 1998 till 2001, the reservoir contact gradually increased by drilling 2 km and 3+ km single lateral wells. This success led to the birth of the MRC well concept in 2002.

In February 2000, Saleri (Saleri 2000) proposed step-change improvements in tight facies wells productivities through significant increases in reservoir contact, which led to the development of maximum reservoir contact (MRC) wells in Shaybah. Multilaterals with fishbone architecture wells were drilled, providing tens of thousands of feet of reservoir contact (Saleri 2002, Saleri et al. 2003). The aggregate reservoir contact in excess of 16,000 ft (5 km) through a single or multilateral configuration defines MRC wells (Saleri 2004). Saudi Aramco applied the first MRC well, in 2002, in Shaybah Field that consisted of the following:

- A motherbore parallel to the structure (3 km long).
- Two multilaterals (L-1, L-2) parallel to the motherbore.
- Six fishbone type laterals (L-3, L-4, L-5, L-6, L-7, and L-8) planned at 30° from the motherbore.

Multilaterals and MRC wells ushered in fresh re-engineering efforts in all disciplines (Saleri 2003):

- Logging While Drilling (LWD) for downhole intelligence
- Real-time Geosteering Technology to place multilaterals in prolific petrophysical zones
- Drilling practices with sophisticated technology in well design, mud systems, circulation methods to minimize well damage and attain theoretical well productivities with longer reservoir contact
- New completion technologies such as inflow control devices (ICD) and inflow control valves (ICV)
- Researching the tradeoffs among complex well architecture (geometry and completion), reliability, well intervention, monitoring and costs
- Investigating the risks and side effects in MRC well performance and operation
- Advanced well testing for MRC wells
- New numerical modeling capabilities for smart and complex completion architecture wells

In 2004, the MRC well concept was extended to other Saudi Aramco oil and gas fields. This technology, combined with active downhole inflow control valves, optimized production from each lateral. In recent years, horizontal and complex architecture including maximum reservoir contact (MRC) wells with smart completions were preferred over the conventional wells in Saudi Aramco.

Aside from drilling new production wells, the MRC concept revolutionized workover practices by utilizing existing assets and converting weak and dead, conventional or single lateral, wells to multilateral or MRC wells. The first smart completion in an MRC well exited from a 5 ½” expandable liner. This well was successfully worked over and converted from a 1-km single lateral horizontal well to a trilateral (MRC) well with a smart completion system inside 5 ½” expandable liners. As a result, in Shaybah, a workover program was initiated in 2004 to improve well productivities by maximizing reservoir contacts. To date, more than 40 wells were converted from single lateral 1-km wells to multilateral/MRC wells.

In an effort to reduce cost and save rig time, Saudi Aramco ran the first swellable packers in an openhole completion of a horizontal well in Shaybah Field. This well was worked over and converted from 1-km single lateral horizontal well to trilateral (MRC) well and completed with a combination of swellable packer and smart completion system. The swell packers were used to provide lateral isolation removing the need for the expandable liner.
The initial completion method selected was open hole for carbonate reservoirs and cased hole cemented with selective perforation strategy for horizontal wells in sandstone reservoirs (Sunbul et al. 2007). Those two initial completion methods were troubled by non-uniform fluid flow profiles resulting in less than optimal well performance.

In 2002, Saudi Aramco applied two new completion techniques in order to increase production and completion efficiency from horizontal and MRC wells. One technique utilized stand-alone mesh screens with passive ICD and mechanical open hole packers while the other utilized expandable sand screens and isolation sleeves. The introduction of these new open hole completion techniques had reduced the time required to complete the well, and allowed an overall completion cost reduction for the passive ICD completion compared to cemented perforated liners (CPL), mainly due to saving rig time (Hembling et al. 2007). The inflow control valves (ICV) were first deployed in 2004 in Saudi Aramco.

The expandable screen completion experienced sharp production decline because of early water breakthrough. The early water breakthrough was associated with non-uniform inflow profiles that induce coning. The stand-alone mesh sand screen fitted with propriety, low velocity flow regulators (ICD) and mechanical open-hole swell packers for zonal isolation (Fig. 1) restricted production from high productive zones to allow the pressure in the wellbore to be lowered to pull harder from the less productive zones. If the well path is near either water and/or gas, ICD will minimize any undesired coning effects that lead to premature water and/or gas breakthrough. The packers are placed based on changes in formation properties as detected from logging while drilling (LWD).

Controlling and managing inflow distribution, along the laterals with one or more of above conditions, will prolong dry oil production, extend the well life, even-out sweep vertically and horizontally, and improve recovery efficiency in the well in a cost effective manner. Widespread application of ICD systems in other Saudi Aramco fields started in 2005. By the end of 2008, more than 200 horizontal wells including multilaterals and MRC wells were equipped with ICD completions in both sandstone and carbonate reservoirs. ICD completions are expected to rise (Task Force, 2008). Over 100 single or multilaterals, and MRC wells have been equipped with inflow control valves (ICV) as well. ICVs are forecasted to be installed in additional MRC and single or multilaterals wells in the future (Task Force, 2008).

ICD and ICV systems are being utilized in selective horizontal wells which meet the following criteria:
- Presence of lost circulation or fracture zones along the lateral
- High reservoir pressure variation along the lateral
- Significant permeability contrast along the lateral
- High frictional pressure losses from heel to toe (heel-toe effect)
- Significant viscosity/mobility variation along the lateral
- Thin oil column bounded by water and/or gas zones with high coning or cusping tendency

The first Slim Smart Completion (SSC) in the world with three ICV was applied, in 2007, in a trilateral sidetrack (Lyngra et al. 2008) completed in the 25-feet thick oil column. The SSC system was developed upon request from Saudi Aramco due to its wide application for re-entry sidetracks out of 7-inch liners in existing wells. The SSC was deployed passing through the post-expanded 5.5-inch inner diameter liner. Figure 2 illustrates the evolution of multilaterals, MRC well architecture and smart well completions in Saudi Aramco.

Modeling of Complex Architecture Wells with Smart Completions
A complex architecture well with smart completions requires a correspondingly sophisticated type of well model to be implemented in the reservoir simulator. The model should be able to determine the local flowing conditions (the flow rate of each fluid and the pressure) throughout the horizontal well, pressure losses along the single or multilaterals and across any inflow control devices. Holmes (Holmes et al. 1998) developed a multisegmented well model, for multilateral wells, that offered a means of modeling complex architecture wells with next generation smart completions. Each segment consisted of a “node” and a “flowpath” to its parent segment’s node. Complex architecture wells with smart completions are also being modeled with surface network simulator coupled with conventional black oil simulator recently.

Saudi Aramco (Su et al. 2007) developed an analytical well equation to model pressure loss across ICD as formation damage (skin). Combining the pressure loss (across ICD) equation with the conventional well equation led to greater numerical stability as all physics problems were solved simultaneously.
New Well Modeling Work flow and Optimization of Complex Wells

Planning and designing of those complex architecture wells with smart completions require extensive and thorough modeling studies to optimize total lengths and configurations, as well as the placement of ICV and/or ICD along the mother bores. Those wells are generally more expensive to drill and complete, their use must be justified and optimized. Realizing the important role of reservoir simulation and the difficulties of modeling and optimizing of these complex wells, Saudi Aramco embarked on a mission, from 2002, to develop advanced well modeling technology to simulate and optimize evolving complex architecture wells with smart completions.

A new industry standard simulation workflow for the complex architecture wells was developed and tested with a service provider (Moreno et al. 2006). As the number of wells with complex configuration with smart completions increased, new challenges appeared in modeling their performances—detailed description of pressure gradients along the wellbore, rigorous representation of the MRC wells in the simulation models, and corresponding calculation of grid-cell connection factors. Several other issues in the reservoir simulation are cross flow in and between laterals, the gridding effect, segmented wellbore and modeling of pressure drops of ICD and ICV. Subsequent study used the same developed workflow but incorporated geologic uncertainty into the complex well configuration (MRC Phase II, 2005). The new developed workflow for simulating and optimizing MRC well design and smart completion is illustrated in Fig. 3. Flow within each segment uses proper flow equations accounting for hydrostatic, frictional, and acceleration caused by valves, channels, chokes and any kind of inflow control devices.

The new workflow would be summarized in five steps: (1) sector selection from the full-field simulation model and choice of well location, and further grid refinement, (2) design of well trajectory and optimization of well placement and architecture under geological uncertainties, (3) analysis of flow profile (from PLT if available) to optimize smart completion design, (4) examination of consequences of geological and mechanical uncertainties, and (5) insertion of optimized well back into the full-field simulation model.

Sector model has its advantages and disadvantages. One shortfall of the sector modeling is in treating its flow boundaries. Inserting the optimized complex architecture well with completion design back into the full-field model can eliminate the difficulty. Then the field control would then take over and the overall impact of this complex architecture well on the field could be evaluated accurately.

Step (2) involves construction of different well architecture, placement, multiple reservoir realizations, and simulated them to map the well response surface. Each configuration is run with a fixed production rate and with either BHP or WHP constraints. The results from those training sets are transferred to a neural network to form a proxy model. The neural network pinpoints the relationship between the input variables: number of branches, branch angles, lengths of laterals, and the cumulative productions from different well architectures. The neural network training develops a proxy model as illustrated in Fig. 4. The genetic algorithm is used to optimize the input variable to reach the maximum or minimum objective function.

Well completions vary from open-hole, perforation, blank pipe, ICD to ICV. The process (Step 3) is similar to well architecture optimization: proxy models created via neural network with genetic algorithm optimizes these controllable parameters. The alternative is to simulate the limited scenarios and select the one with best results. The optimized completion includes the best complex architecture and placement of ICD and/or control strategies of ICV.

Furthermore, the uncertainty framework can address the uncontrollable reservoir uncertainties such as faults, fractures, anhydrite barrier, permeability variations, pay thickness, aquifer strengthen and other reservoir parameters. Modeling of uncertainty parameters could be in discrete realizations or in continuous ranges. To address the probability and risk, a proxy model can be built with the neural network or Response Surface Model (RSM) and coupled with Monte Carlo simulation method. The P10/P50/P90 of well performance given by corresponding complex architecture well and completion models could be identified.

Case1: Planning of MRC Well Architecture Reflecting Uncertainties in Geological Realization

The sector model including Well A (Fig. 5) is extracted from the full-field simulation model with 250 meters areal gridblocks. The sector model contains 18 wells, and refined to 350,000 active cells with a 50m by 50m resolution with 26 layers. In this case, the objective is to optimize the original architecture of the well which composed of five laterals. The uncertainty of the amount of the anhydrite barrier in Layer 2 of Zone 1 is generated stochastically in six realizations of permeability, as shown in Fig. 6.

The parameters optimized for Well A MRC include: 1) number of laterals, 2) length of each lateral, and 3) angles of laterals from the motherbore. Figure 7 shows simulated production profiles given by different geological
realizations. The difference in performance from the 6 realizations is quite significant. The well was designed for the median realization, but it is not effective in other realizations. Based on these findings, a methodology was developed to address the issue of assessing the impact of uncertainty in geological definition on well performance.

Methodology: The final workflow developed for the study is shown in Figure 8 and the various stages are described. Here is the outline of the workflow:

1. Extraction of sector model
2. Optimization of well architecture in all geological realizations
3. Derivation of one configuration optimum for all geological realizations

Once the area of interest inside a full-field model was defined; the full-field model was run and the flow of fluids across the boundary, between the area of interest and the rest of the model, were stored at every time step into a flux file. Fluxes were generated for the six stochastically generated geological realizations using the same well configuration and production targets for the sector. Then the workflow (Moreno et al. 2006) was conducted for each geological realization individually. The optimized six well architectures are shown in Figure 9.

Results: Well optimization performed with each geological realization resulted in different well configuration. To decide which of the resulted configurations had a higher probability for successful performance, a risk assessment was performed. Configurations, three, four, and five were identical; therefore, the performance assessment was conducted for four configurations in the six geological realizations. Graphical illustration of the results is presented in Figure 10. The objective function (cumulative oil production) was normalized in percentage for performance assessment. The well configuration that gave overall highest percent of performance in all 6 geological realizations was considered as the final optimum.

Figure 10 shows that configurations 3 and 6 gave overall high percent of performance in all six geological models. Although the configuration 3 shows the excellent performance in the geological models 3, 4 and 5, this configuration is not good in the geological realizations 1 and 2. For configuration 3, there is more than 30% of probability to lose up to 40% of potential production. The variation in probability of performance is quite wide with configuration 3. This range in probability of performance is referred to as a confidence interval. Optimization process could narrow the confidence interval. Well configuration six is the final with highest overall 87 percent of performance and smallest confidence interval (Figure 11).

Case 2: Optimization of Well Architecture and Completion in a Sandstone Reservoir
This clastic reservoir consists of meandering fluvial channels running from East to West. Transversal sand dunes aligned North-South with interspersed playa and sand sheets. This reservoir is very heterogeneous with contrasting geological facies. Pressure support from peripheral water injection was not effective and experienced water channeling. A reservoir simulation model was used to assess well location for both producers and injectors. Emphasis was placed in development of well architecture, placement and completions.

Methodology: A sector model was extracted from the north part of the full-field model. Well segmentation simulation for open-hole completion was performed for single horizontal, slanted, dual-lateral and trilateral wells. No neural network or genetic algorithm was performed as the choices of well configuration were limited. The best well configuration was selected based on well performance. The simulated flow profile at the wellbore was then visualized and analyzed to assess the need for completion. Several ICD placements and ICV were simulated for performance comparison.

Results: The optimum well configuration was an extended horizontal well with 3.6 km in length and equipped with ICV (Figure 12). Multilateral configuration intersecting interconnected sand bodies are not likely to improve well performance. Dual laterals improve the probability of crossing more high permeable sands but their performance is very similar to long horizontal well. Horizontal wells perform better than slanted wells in delaying water breakthrough. The effect of ICV on production profiles is illustrated in Fig. 13. The well watercut is very low with the extended horizontal with ICV as shown in Fig. 14. Flow profiles given by ICV modeling are presented in Fig. 15. Flow equalization by ICD was not effective to improve the well performance. The best ICD configuration had similar performance to the open-hole completion as shown in Figure 16.

Case 3: Well Optimization with ICV Completion using a Shortened Workflow
A shortened workflow with simulation of limited well architecture scenarios and selection of the best case is more practical without using the neural network or optimization functions. This MRC producer was planned to complete in a naturally fractured carbonate reservoir. The original plan was for five laterals with a total length of 5.5 km. A
shortened work flow was used to evaluate the benefit of ICV installation. The well modeling used the coarse grid full-field model without sector or grid refinement.

The complex well architecture modeling with ICV completion incorporated in the in-house simulator was utilized to simulate the action of ICV in each lateral of the well. When watercut in each lateral reached 50%, the ICV would activate and reduce the total fluid by half in the offending lateral and allocate the required well oil rate to other laterals. The flow profile and performance of the five laterals were analyzed to eliminate the laterals with low or insignificant contribution. The quick optimization produced an optimum trilateral well configuration.

**Results:** The original MRC design with 5 laterals of total length of 5.5 km was optimized to trilaterals with 3.5 km as shown in Figure 17. Optimized well performance showed that the ICV could reduce significantly the cumulative water production and increase the cumulative oil production substantially throughout the well life (Figure 18). The impact of ICV on flow profiles in Lateral-1 is shown in Figure 19.

**Case 4: Well Architecture and Completion Optimization in oil rim development**
A reservoir with thin oil rim under gas cap poses a real challenge in well configuration and completion. The fluid movements are sensitive to well drawdown and the heterogeneity in low matrix permeability which is complicated by existence of fractures. Field development using MRC well is essential in obtaining good well productivity and minimizing pressure drawdown. The well configuration, placement, completion and operating conditions are critical for overcoming gas-out effects. To screen efficiently the different possibilities of well configuration, placement, completion and operation conditions in the complex reservoir, well modeling within a reservoir simulator was employed.

**Methodology:** Mechanistic sector models were created to investigate the different well designs/placements and with different permeability/fracture configurations. Seven well configurations, which included base case trilateral MRC, deep MRC, deepest MRC, deepest MRC with defense line, stacked laterals, stacked MRCs and dual MRC wells, were evaluated as shown in Figure 20.

The best well configuration, that delays the gas breakthrough, had the longest plateau duration, the highest cumulative oil production with or without GOR constraints, and could sweep the bottom part of the reservoir in the good and low permeability scenarios, was selected. Next, the impact of friction losses for the well type configurations was assessed, especially for long MRC wells. After the well type was selected, different well completions and policies were investigated.

The contribution of flow with gas arrival that highly affects the well productivity was analyzed per laterals to determine the type of completion. A multi-segmented well modeling option was used to obtain fluid rates and pressures along different wellbores. Downhole equipment such as ICV, ICD and blank pipes were evaluated at different designs and objectives. Then, the most promising well configuration and completion were implemented in the full-field model.

**Results:** Dual MRC wells produced the best scenario, because they could extend the plateau duration under high and low permeability scenarios. They reduced/controlled GOR, enhanced the sweep, doubling the reservoir contact, acting as defense line against gas production/coning, and accessing deeper into reservoir. The sweep efficiency added by a dual MRC well configuration is highlighted in Figure 21 as the gas moves more uniformly. Simulation results show that the whole well length contributes to flow with or without friction losses effect. The results of implementing ICV are shown in Figure 22.

The typical performance of a well without ICV when approaching GOR limit would dramatically increase well drawdown. The well would lose its production potential quickly and would need to be shut-in once it reached well/group GOR limit. Different smart completions were evaluated, and proved that ICV was a necessity. Blank pipes were recommended as mitigation to fracture impact and permeability contrasts which drastically affect well performance. ICD implementation should be evaluated in a well by way basis only when permeability and fluids profile (PLT) logs are available and clearly shows anisotropy.
Conclusions

1. Our experience in employing complex architecture wells has improved well and field production performance and pushed the limits of modeling capability for complex well architecture wells with smart completions.

2. A new industry-standard well modeling and optimizing workflow has been developed and utilized to design and optimize the fit-for-purpose complex architecture well with smart completion under geologic uncertainties.

3. The developed workflow made possible to model and design complex architecture wells with smart completions to achieve optimum performance. Four field cases are presented.

4. Well modeling and field application results show that ICD were successful in achieving evenly distributed flow profile along horizontal laterals, alleviating the impact of fractures and turning wells into good producers.

5. Modeling and field application of wells equipped with ICV show reduction in water production in all cases and increase in oil production in selective cases.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>GOR</td>
<td>Gas-oil ratio, Scf/STB</td>
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<td>ICD</td>
<td>Inflow control devices (Equalizers)</td>
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<td>ICV</td>
<td>Inflow control valves</td>
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<td>LWD</td>
<td>Logging while Drilling</td>
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<td>ML</td>
<td>Multilaterals</td>
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<td>MRC</td>
<td>Maximum reservoir contact</td>
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<td>NWM</td>
<td>Near wellbore modeling</td>
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<td>PIF</td>
<td>Production Increment Factor</td>
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<td>PLT</td>
<td>Production Logging Tool</td>
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<td>SL</td>
<td>Short lateral</td>
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<td>SSC</td>
<td>Slim Smart Completion</td>
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Acknowledgments

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References


Figure 1—Horizontal well equipped with ICD/Equalizers with zonal packers

Figure 2—Evolution of multilaterals, MRC well architecture and smart well completions in Saudi Aramco
Figure 3—Developed workflow to design and optimize a MRC well with smart well completion

Figure 4—Neural network training sets to optimize the MRC well design to be equipped with Inflow Control Devices
Figure 5—An MRC well in the sector model

Figure 6—Permeability distributions of Layer 2 to represent anhydrite barrier in the reservoir. Dark blue color represents a minimum amount of anhydrite acting as a barrier.
Figure 7—Well performance in different geological realizations

Figure 8—Simulation and optimization of a MRC with the neural network
Figure 9—Optimum configurations for the six geological realizations of anhydrite barrier

Figure 10—Performance assessment of four complex architecture wells
Figure 11—Final optimum configuration for the MRC well after assessment

Extended Horizontal Well

Figure 12—Optimized 3.6 km single horizontal well with possible ICV locations (Case 2)

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Figure 13—Optimization of well architecture with ICV is illustrated by well oil production rate (Case 2)

Figure 14—Optimization of well architecture with ICV is illustrated by well water cut (Case 2)
Sections at the heel compensate for the choked areas.

Figure 15—Effect of ICV on production profiles (Case 2)

Figure 16—Flow profiles with and without equalizers (Case 2)
Figure 17—MRC well with five laterals is optimized to trilaterals by reservoir simulation (Case 3)

Figure 18—Impact of ICV in optimized trilaterals (Case 3)
Figure 19—Water and oil production profiles along Lateral 1 (Case 3)

Figure 20—Types of complex horizontal well architecture investigated in Case 4
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<th>GOR, Mcf/STB</th>
<th>Pressure, psi</th>
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**Figure 21**—Best sweep of bottom oil was achieved by dual MRC well (Case 4)

**Figure 22**—Positive effect of ICV in Case 4