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1 Introduction

This Quarterly Report covers the following topics of the Downhole Commingling Research project:

- Literature search (see key references at end of report)
- Types of downhole commingling methods and technologies

Commingling in oil and gas wells refers to the simultaneous production of hydrocarbon from multiple reservoirs through a single production conduit.

The traditional methods of exploiting multiple reservoirs from one wellbore are to either:

- Develop the reserves sequentially from the bottom up, or
- Use multi-string completions to maintain segregation

The disadvantages of the first method are that it can take a long time to exploit all the reservoirs, and the sequencing of production often precludes use of secondary and/or tertiary recovery methods that have the potential to improve the fraction of hydrocarbons that can be recovered.

The disadvantage of the second method is that productivity from the individual zones and from the well in total can be restricted because the size of the tubing is limited by the size of the casing. Casing size can be increased to accommodate the larger tubing required for optimum production, but this is a costly option.

When two zones are commingled without control, the zones are most likely to produce in a sub-optimum manner due to the differences in pressure, productivity index, gas-oil-ratio (GOR), and water production. One zone may crossflow into another, and gas or water breakthrough in one zone may limit the oil production in the other, reducing ultimate recoveries.

Commingling multiple zones using conventional technology has had limited success, typically in the following reservoir types:

- Reservoirs in the declining stage of production with fairly low production rates, for instance the Austin Chalk and related reservoirs
- Wells penetrating closely adjacent reservoirs of similar fluid compositions, gravity and pressure gradients, e.g. in parts of Lake Maracaibo in Venezuela

The drive mechanisms for the commingled reservoirs were the same, typically water drives and gas drives, and were not an obstacle in planning the commingling projects. Results were positive in that production of the combined reservoirs appeared to be almost the same as the sum of the individual production of each zone based on comparison of commingled and non-commingled wells.[1]

In many of the more prolific hydrocarbon basins, multiple reservoirs are encountered stacked one above the other. Government regulations and good petroleum practice prescribe that the production of conventional oil and gas from distinct reservoirs or pools must remain segregated in the wellbore, which can have a negative effect on economics by deferring production of one or more intervals. The purposes of maintaining segregation of oil and/or gas in the wellbore are:

1. To avoid the potential for wellbore and/or reservoir conditions that may adversely affect ultimate recovery, e.g. crossflow of reservoir fluids
2. To facilitate enhanced oil recovery (EOR) operations such as water flooding or gas injection targeted towards specific intervals
3. To maintain the ability to gather data on an individual reservoir as the basis for reservoir management and, in some cases, royalty determination
4. Concerns about fluid compatibility
5. Minimization of interventions

On the other hand, commingling can provide very large increases in net present value for the following reasons:

1. A higher production plateau and faster cash flow
2. Ability to produce hydrocarbons from reservoirs that may be uneconomic to produce on their own, thus increasing ultimate recoveries
3. Fewer wells, less infrastructure and lower capital costs
4. Lower operating expenses
5. A smaller environmental “footprint” due to fewer locations

The economic benefits to the operator and, in the case of points 2 and 5 above, to the regulatory authorities of commingling are clear, especially in high cost field development applications; however, several practical inter-related issues must be considered before approving commingling:

1. Allocation of production to different reservoirs, which can affect reservoir management decisions and, in some cases, royalties.
2. Prevention of crossflow between reservoirs
3. Ability to exclude production of unwanted effluent (water or gas)
4. Well integrity and flow assurance
5. Ensuring the compatibility of reservoir fluids

These important factors beg the question of how to better define the circumstances under which commingling can be permitted without a loss of reserves as discussed in the next section.

2 Technologies and Methods

During the 1960's and 1970's, when many reservoirs in Lake Maracaibo, Venezuela that were producing medium crudes were in decline, a drive to commingle multiple horizons was undertaken to rejuvenate and improve the performance of declining fields and to increase reserves.

Production logs (PLT), capillary gas chromatography (CGC), and separator testing were used to quantify the production of the individual zones related to total production. Unfortunately, CGC can only be applied if there is significant difference between the compositions of the different crudes being produced, which is not the case in Lake Maracaibo. A method to calculate the composite inflow performance relationship (IPR) was used which took the following into account:

- The IPR curves of individual reservoirs
- The mechanical configuration of the well
- The separation (distance) between the producing zones and the associated fluid gradient between them
- The distinct fluid properties of each reservoir

This method was effective in estimating the composite IPR based on the IPR curves of individual reservoirs to predict the performance of a commingled well. The calculation procedure used can generally show the possibility of crossflow among zones. After accumulating and comparing data to identify zones with oil and gas of similar compositions, each zone was separated by a casing packer and a sliding sleeve. An attempt to create similar flow conditions entering the tubing from each zone was accomplished by placing a calibrated pre-set downhole regulator in the sliding sleeve in front of the zone having the highest pressure, so that the downstream pressure of the regulator was the same as the depth-adjusted pressure in the tubing producing from the zone with the lower pressure. Although the application requires each zone have similar general characteristics such as oil gravity, zones may have slightly different gas-oil-ratios, on the order of 15%, without an adverse effect on the pressure in the tubing.[1]

The procedure demonstrated that the right selection of reservoirs with somewhat similar characteristics can be commingled, but the method and procedure required constant monitoring of surface pressures and flow rates of the commingled production to ensure that the production rate almost equaled the combined individual rates of the two zones. The best results of commingling were when similar static pressure zones were combined, or when a lower static pressure zone had a higher productivity index (PI). Further successful commingling projects were undertaken in Lake Maracaibo in reservoirs with water and gas drives, with a focus on monitoring volumetric replacement balance, delaying fluid breakthrough and maintaining a high producing rate. The technique was also used to manage fluid velocities to control reservoirs with sand production and coning problems.

These methods were generally successful in minimizing deferred production, achieving high ultimate recoveries, and enabling production from sands that otherwise may have been bypassed in wells that, although in decline, were still producing between 600 to 1,000 bopd. No attempts were made to commingle zones of wells that had a mixture of high pressure/high production rates and low pressure/low production rates to avoid the possibility of crossflow. Additional commingling projects were run with reservoirs with high rates of production; however, commingling efforts were not successful when the high rates were very different from one other.

3 Disadvantages in Early Commingling Practices

An obvious disadvantage exists when downhole regulators with fixed differential settings are placed in sliding sleeves to control the flow from commingled producing zones: in a declining reservoir, dynamic parameters such as the PI and water cut, which cause changes in flow rates over time, make a fixed setting in the downhole regulator inefficient. To adjust the regulator to new flow and pressure conditions of a reservoir, the regulator (and tubing) must be physically retrieved and reset. Well interventions in response to the natural changing conditions of the reservoir result in deferring production, high operating costs and adverse economic impacts. With time and the naturally changing parameters of a producing well such as pressure, PI and water cut, effective commingling cannot continue for long periods while using a mechanical downhole regulator.

4 Advent of Intelligent Well Systems

The advent of intelligent well systems (IWS) using remotely controlled sliding sleeves (also referred to as downhole regulators, valves or chokes), tubing and annulus pressure gauges, and, in some cases, downhole flowmeters and temperature gauges, offers the promise of independently monitoring and controlling production from each zone to optimize a well's flowing parameters. IWS technology, also known as intelligent well completion (IWC), is now being widely implemented worldwide and has started to deliver on the promise of enabling reservoir management and optimizing production. In some wells, production rates have doubled following IWS implementation as indicated in a couple of the examples below. In other cases, IWS functionality has enabled operators to develop reserves that otherwise would have been overlooked.

An IWS is capable of:

- Collecting, transmitting and analyzing completion, production, and reservoir data, and
- Taking action to better control well and production processes.

The value of intelligent well technologies thus comes from both the capability to actively remotely modify zonal completions and flows through flow control, and to monitor the response and performance of the zones through real time downhole data acquisition. IWS has been utilized to optimize completions in commingled, multilateral, sand control and electrical submersible pump (ESP) completions with documented success.

5 Examples of IWS Relevant to Commingling

Three deep water gas fields in the Gulf of Mexico, Aconcagua, Camden Hills, and King's Peak, are using IWC technology to optimize commingled subsea development of a marginal reserve base. These fields are located in Mississippi Canyon and Desoto Canyon blocks in from 6,200 to 7,200 feet of water. Eight of the nine production wells in this three-field project are completed as intelligent wells, making it perhaps the largest field-wide deployment of intelligent completion technology in the world. The use of intelligent completion equipment to optimize the reservoir is critical to the economic success of these fields, as it enables:

- Gas production from multiple zones to be commingled
- The well to be reconfigured to shut-off water production, preventing crossflow that could damage ultimate recovery, without the requirement for well intervention.
- Development of a field that otherwise would not have been economically feasible to produce, thus adding net reserves and royalties.[2]

In the large Agbami field offshore Nigeria, IWCs are being utilized to optimize field performance from multiple commingled zones. IWCs with downhole control valves and interval control valves (ICVs) are installed. The system provides zonal information, such as pressure, and enables control of production from, and injection into, the completed sub-reservoir zones. Reservoir modeling indicates most wells have direct incremental recovery by use of ICVs because of the ability to manage individual zones. The ability to optimize zonal contributions by collecting information on zonal drawdown, productivity index, and production data helps to maximize well production and ultimate recoveries. It will also help to sustain plateau production and minimize decline rates.[3]

In multilateral wells where the laterals contact different portions of the same reservoir, gas or water breakthrough in a lateral can negatively oil production. The Norwegian state oil company Statoil chose to use IWS in their Glithne A-H6 to remotely control flow from either lateral at the junction without rig intervention in anticipation of eventual water breakthrough. Additionally, Statoil hoped to gain valuable reservoir and production data from the downhole sensors. Statoil selected a Baker Oil Tools in Force IWS with hydraulic control model (HCM+) remotely controlled hydraulic sliding sleeves for open/close flow control. The HCM+ sleeve is a hydraulically operated downhole flow control device that is operated using two control lines from the surface. The balanced piston concept is designed to help ensure reliable operation at actuation forces of up to 17,000 pounds. In about 50 installations worldwide, to date there has not been a reported field failure of the HCM+. The end result in this example was a successful dual lateral well with remotely controlled lateral production that would have been uneconomical to drill and complete using a conventional configuration of two single lateral wells, thus adding net reserves. The well continues to produce, and the HCM+ has been operated successfully numerous times.[4]

In addition to optimizing production from multiple reservoirs in a commingled situation, IWS enables operators to monitor and remotely adjust the injection rate into multiple zones of a water injection well, thus helping to manage water breakthrough and increasing oil recovery. When these water injection wells are in deep water, the OPEX associated with intervention to optimize water injection can cost millions of dollars and be prohibitively expensive.

Many wells in deep water are drilled in environments where the producing formations require sand control completions to maximize well productivity. In injector wells, sand control can be critical during shut-in periods, which can occur frequently, to minimize sand production and potential formation plugging.

The Marlim Sul field in the Campos basin offshore Brazil has been producing oil and gas since 1994. It is one of the world's largest discoveries in the past 20 years and is part of an enormous offshore industrial complex operated by Petrobras. The reservoirs of the Marlim and Marlim Sul fields are described as sandstone without water influx and thus require substantial water injection for pressure maintenance. Historical experience has verified that the reservoirs are unconsolidated and require sand control for both injectors and producers. IWS held the potential for extending and expanding the basic well completion function to better serve the needs of reservoir management. Standard methodology for the field would have been to complete the reservoir as an open-hole gravel pack and inject into all zones uncontrolled from the surface. IWS technology provided the ability to monitor, in real time, the injection rate into each interval and then make changes to the injection rates to optimize production, thus:

- Mitigating water breakthrough
- Managing reservoir sweep and pressure support
- Avoid production rates that could create excessive sand production.

The IWS chosen for this application, a Baker Oil Tools in Charge Fully Electric IWS, provides integrated pressure, temperature and flow rate monitoring with remote downhole control of each interval from a single control line from the surface. A key driver for choosing this system was the single control line, which minimized the amount of subsea integration required to successfully install an IWS. Based on measurements generated downhole, injection rates can be adjusted by changing the position of the intelligent production regulators (IPRs), downhole chokes that can be remotely adjusted from the surface via the single control line.[4]

In the North Sea, Shell U.K. has applied intelligent wells in its Tern field to enable controlled commingling of the Lower Ness/Etive and the Triassic Broom/Rannoch/Upper Ness formations. Previous development of these reserves was by sequential development of the more prolific Lower Ness/Etive followed by the Triassic Broom/Rannoch/Upper Ness. The application of intelligent well technology enabled production from the wellbore to be switched between the Lower Ness/Broom and the Triassic formations. Selective testing of the two formations allowed production splits and water cuts to be obtained without the requirement of production logging. Estimated accelerated oil production of some 430,000 bbl and estimated incremental oil production of 85,000 bbl are expected using the proposed intelligent well completion.[2]

Mobil Producing Nigeria Limited (MPN) drilled a long-reach producing well in the Usari field which was completed as an IWS commingled producer in three of the seven discovered zones. Each of the three zones was equipped with downhole gauges, which provide the capability to properly manage the recovery of reserves from each individual zone. The average first-year rate was approximately 11,000 BOPD, whereas a single producer would have only provided about 7,000 BOPD.[5]

Producing wells in eastern Ecuador usually contact two to four productive zones. The Government regulatory body has historically restricted commingled production from these zones; their concerns were that commingled production will lead to loss of hydrocarbon resource by crossflow, excessive draw-down and inefficient production allocation to producing horizons. The installation of a TWS completion addressed these concerns. The intelligent well was designed to provide real time monitoring of each producing horizon. Adjustable chokes combined with surface controlled sliding sleeves from Baker were chosen for the IWS. The monitoring system provides bottomhole pressure and temperature of both zones as well as flow rate and water cut of the lower zone. Combining the bottomhole flowing data with three-phase flow measurement at the surface, the operator is able to accurately allocate well production to each of the producing intervals and adjust flowing parameters from each zone to eliminate crossflow, thus satisfying regulator concerns.[4]

Similar to the Gulf of Mexico, where well production is often enhanced with the installation of an ESP, a dual-reservoir completion using an IWS and an ESP in a high-rate well was deployed in one of the large carbonate fields in Saudi Arabia. The ESP pumped the oil to a centralized processing facility far away from the well through a two-zone smart well completion that remotely controls fluid inflow from each of the two laterals. This completion enables commingled production from two reservoirs while balancing flow contribution from each reservoir and avoiding crossflow. This completion uses a downhole hydraulic disconnect tool with an integral anchor assembly to connect the upper completion incorporating the ESP system with the lower completion that incorporates the IWC. This integrated system provides the flexibility to control inflow from each reservoir in the future as the flow regimes change.[6]

6 Final Thoughts: The Potential for, and Reliability of, Intelligent Well Systems

Reservoir drive mechanisms such as water drive, depletion gas drive and gas cap drive are key factors in the production and ultimate recovery of oil reservoirs. Commingling multiple reservoirs with different drive mechanisms without control gives rise to lower combined rates, crossflow from higher pressure to lower pressure zones, loss of reserves in one or more of the reservoirs, and/or production deferral. With the evolution of IWCs, commingling of reservoirs with different drive mechanisms becomes a possibility, since:

- Reservoirs are monitored at the sand face with pressure sensors
- Production rates and pressures can be controlled by opening or closing the control valves to varying degrees at each producing horizon to meet the ever changing conditions (pressure, rate and water entry) in each reservoir.

The following are key features and benefits of IWS:

- Enable selective zonal isolation when multiple sleeves are used.
- Eliminate well intervention; the opening and closing of the sliding sleeve/valve is controlled from the surface via hydraulic control lines
- Reduce risk associated with intervention
- Accelerate revenues and royalties by maintaining production and rig uptime
- Reduce wellbore storage effects during transient testing, thus saving production downtime
- Increasing ultimate recoveries and royalties by enabling production of intervals that would be uneconomic to produce on their own.

Clearly, continuous surveillance and monitoring is necessary to manage the commingling program and ensure high recovery factors.

The reliability of IWCs, including key components such as downhole sensors and the hydraulic controls associated with intelligent tubing completions (ITCs), is key to achieving the promise of higher ultimate recoveries. The major service companies that manufacture and service intelligent well equipment appear to have achieved an average system reliability of about ninety percent through such design techniques as:

- Use of field-proven high strength non-elastomeric seals.
- Flow slot and port configurations designed to be resistant to erosion
- Use of tougher compounds for hydraulic lines.

The population of IWCs this 90% reliability figure is based on comprises:

- Halliburton: 480 installations
- Baker Hughes: 190 installations

In many applications, IWS must be actuated repeatedly under severe well conditions; hence, ensuring sliding sleeve reliability is an important part of the reliability equation. Sliding sleeves (also referred to as downhole regulators, valves or chokes) are tools run as part of production tubing in oil and gas completions to provide a means of communication between the tubing and the annulus for fluid circulation or selective zone production or injection. Sliding sleeves have long been used in both single and multiple well completions to permit flow from individual zones into the tubing when the well produces sequentially. As the name implies, the sliding sleeve is a ported or slotted tool with an internal sleeve which can slide up and down, with seals to seal off the ports. With sliding sleeves having evolved into a key component in ITCs, these sliding sleeves are hydraulically controlled from the surface and are designed for selective production control (as opposed to simply being open or closed) based on changing flow conditions.

Sliding sleeves are reliable tools when used with the care required with any equipment exposed to oil, gas and water. In many completions where wells are produced sequentially, sliding sleeves are left for months or years without being activated, with drilling fluid in the annulus behind the sleeve. Good practices to help ensure reliable operation are to:

- Flow every zone after the well is completed to test the sleeve and to ensure that the outside of the sleeve does not become caked with mud
- Have lubricating fluid (e.g. oil) behind the sleeve so that later activation is facilitated.

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