

Third Quarterly Report to:
Minerals Management Service



for

Downhole Commingling Research

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1 Commingling of Reservoirs with Different Drive Mechanisms

Oil and/or gas production flows from a reservoir due to a difference in pressure between the reservoir and the surface. The pressure and consequently flow in a reservoir emanate from a “drive mechanism” which is either one that is inherent in the reservoir or one that is influenced by external forces. These drive mechanisms are:

- Depletion drive/solution gas drive
- Gas cap drive
- Aquifer (water) drive
- Water and/or gas injection
- Rock compaction

In the deep waters of the Gulf of Mexico, rock compaction is the principal drive mechanism, although all drive mechanisms exist. Designing an intelligent well completion (IWC) considers the flowing bottomhole pressure (P_{wf}) and static pressure of each producing zone. By means of a composite IPR curve of all reservoirs, the optimum pressure into the wellbore from the producing reservoirs is determined; this pressure is then controlled by the inflow control valve in the completion. The downhole pressure and temperature monitoring and flow allocation enabled by intelligent completions facilitate reservoir management regardless of drive mechanism, flowing characteristics, productivity index (PI), gravity, temperature and pressure². IWC systems offer the ability to restrict flow or choke each completed reservoir, to shut off crossflow between reservoirs, and to exclude production of unwanted effluent (water, gas), thus enabling management of different drive mechanisms in multiple IWC. As noted earlier in the report, use of traditional completions does not provide this real-time reservoir management capability, leading to less than optimum recovery from one or more reservoirs.

2 Reliability of Intelligent Well Systems (IWS)

An IWC comprises two principal components in the system an inflow control valve and a feed-through isolation casing packer. Feed-through isolation casing packers ensure individual zone control and segregation of reservoirs, and incorporate feed-through facility for control, communication and power cables.

Casing packers have been used for decades with a basic sealing principle which has not changed, but material standards for packers have evolved to meet varying production characteristics such as fluid composition, temperature and pressure. Whether permanent or retrievable, packers have a reliability factor of 99%.

An inflow control valve (ICV), or flow control device, is a component based on a sliding sleeve design. These valves are driven by hydraulic, electro-hydraulic or electric systems, and can be binary (i.e. be either open or closed), have multiple degrees of opening, or be infinitely variable. ICVs with their intelligent means of operating were derived from the sliding sleeve (which has been in the oil and gas industry for as long as casing packers), to enable circulation from the casing annulus to the tubing and to produce multiple completion zones sequentially. While it is impractical to run long-duration laboratory and field tests to qualify the systems for longevity before installation, the industry has set a high reliability target: a 90% probability to survive 10 years for actuators and a 90% probability to survive 5 years for monitoring systems. The challenge is to achieve and to confirm the high reliability of intelligent completions, particularly in the harsh environments in which they are frequently installed.

The industry has made extensive studies of the design improvements required for reliable IWS. Much of this work is focused on the design phase, using tools such as failure mode and effects analysis (FMEA) and reliability qualification testing (RQT)¹⁴ including failure mode testing (FMT) and accelerated lifetime testing (ALT)¹⁵. The implementation of these techniques in the 1980's and 1990's led to improvements in system longevity, but there still remained room for improvement¹⁶. During the relatively early period of permanent monitoring installations in the mid-1990s, only 80% of permanent gauge systems were still operational after 2 years. From 1995 to 2000 reliability improved significantly, with 90% of installations still operating after 2 years. This still left reliability below the industry-established target of 90% probability of survival after 5 years¹⁷.

The rapid uptake of IWS since 2000 increased efforts to improve reliability, and a holistic approach was often used to realize further improvements. A traditional product design approach considers IWS delivery in three discrete and disconnected steps: design, manufacture and installation. An improved product line management system is to consider the product life cycle as an iterative process with formal management systems that link each stage.¹⁶ Central to these systems is methodical record keeping and comprehensive analysis of system operation and any failures on every installation. By applying this holistic approach to the permanent monitoring product line, the latest generation of systems has shown impressive improvement in reliability. Figure 1 shows a survival plot for different permanent gauge systems installed between 1996 and 2005, in part due to deployment of a new dry-mate sealing technology, which has resulted in over one hundred fifty permanent gauge installations without a single failure. This new connector technology was developed after analysis identified connectors as a major cause of failure in permanent gauge systems¹⁸. Under the project lifecycle management process (PLMP), the engineering teams at major service companies instituted a training program before completing a client installation. During the first one hundred fifty installations, sixteen "best practices" and three "lessons learnt" have been recorded. Without this complete system approach to introducing this new technology, this track record would not have been achieved.¹⁶

3 Improved Recovery and Economics for Intelligent Well Completions (IWC): Case Study in the Gulf of Mexico

Economics will obviously play a major role in applying commingling methods to multiple well completions. The Na Kika complex provides an interesting case study of how intelligent completions can be driven by economic considerations in the Gulf of Mexico.

The core Na Kika development comprises five moderately sized (20 to 100 MMBoe) fields containing both oil and gas reservoirs. Individual reservoirs in each of the fields contained recoverable reserves as small as 10% of the field totals. Two of the five fields at Na Kika, Ariel and Fourier fields, feature multiple stacked pay sequences, requiring stacked completions to enable an economic development concept. Stacking multiple completions in a single wellbore carries risks such as differential depletion, crossflow or early water breakthrough requiring costly well intervention; moreover, as is common in Gulf of Mexico fields, reservoir uncertainties existed in terms of compartmentalization, proximity and connectivity between gas and oil-bearing reservoirs, and aquifer size. Intelligent well technology was employed in four of the ten Na Kika wells to manage the production uncertainties associated with commingling and to avoid well intervention¹⁷. Required functionality of these wells included competent sand control with low completion skin, remote zonal control, and continuous pressure/temperature monitoring capability for each zone. The functionality enabled producing reservoirs to be commingled or isolated as well as reservoir diagnosis to be performed remotely from the host facility, allowing optimal assessment of reservoir drainage and depletion management as well as improving economics¹⁹.

In the extreme water depths at Na Kika, drilling and completion costs on the order of \$50 MM per well for a single-zone completion provided a significant argument for optimization by combining multiple completions into a single wellbore. The generally accepted means to produce multiple pay sections in a single wellbore are listed below in order of decreasing capital investment over the well life:

1. Single-zone completion with future up-hole recompletions
2. Multi-zone “selective” completion, requiring future through-tubing intervention
3. Multi-zone IWC
4. Uncontrolled commingled completion of multiple zones

While uncontrolled commingling requires the lowest investments over time, a single intervention to isolate one of the producing intervals increases the well cost beyond that of an intelligent completion that can shut in zones remotely. In addition, completions for uncontrolled commingled wells usually lack the pressure/temperature monitoring capability of individual zones and thus cannot detect crossflow between zones or reservoirs.

In the Ariel and Fourier fields, subsurface studies indicated other potential issues, such as differential depletion between zones, fluid incompatibilities, and timing of water breakthrough from uncontrolled commingling. There is also a certain amount of inherent uncertainty in depletion and water forecasting. The capability to remotely monitor and shut in individual producing intervals alleviates these concerns, adds to ultimate recovery and improves economic returns through:

- Optimal depletion management

- “Managed” commingling of multiple zones in a wellbore while preventing crossflow on shut-ins
- A lower producing stability threshold through commingling of two or more zones than for individual zones
- The capability for pressure build-up tests on one zone to be conducted while producing the remaining zones

Simulations on the Fourier field indicated that the capability to commingle zones in a controlled manner could yield an increase in ultimate recovery of approximately 12% besides improving economics and eliminating the cost and risks associated with well interventions¹⁹.

4 Control of Water Breakthrough Using Intelligent Wells

Analytical methods such as nodal analysis that attempt to optimize the production of an intelligent well are fast methods that can be applied in real time; however, they only enable optimization for a static moment and cannot predict the dynamic behavior that occurs in a wellbore when, for example, a second phase such as gas or water breaks through at one of the completions, which changes the mobility from the reservoir into the wellbore and the flow regime in the wellbore. Detecting and quickly reacting to the moment when a change in the production regime occurs is important, as this is the time for the well production strategy to be adjusted to maximize oil production, minimize gas or water production, and manage reservoir depletion. As noted above, traditional methods for commingling suffer from limited flexibility and excessive costs in terms of well intervention to effectively manage production optimization from each reservoir. On the other hand, continuous changes in the dynamics of an intelligent well can be detected and managed through adjustments to the in-flow control valves without well intervention.

The well HRDH-A12 in the Ghawar field in Saudi Arabia, is the first maximum reservoir contact (MRC) multilateral (ML) well equipped with an IWC. It was drilled and completed as a trilateral selective producer with a surface-controlled variable multi-positional hydraulic controlled system. After analyzing the reservoir data, IWC solutions were evaluated to meet reservoir and production main objectives, such as:

- Sustain well productivity
- Improve sweep efficiency
- Provide selective control of multiple laterals
- Manage water production
- Minimize production interruptions

The intelligent completion used three variable downhole flow control valves designed to provide control of the inflow from each open-hole section of the well (Figure 2). These valves operate as downhole chokes to restrict or completely shut off production from any interval with increasing water cut over time. The completion also was designed to remotely control zonal production, obtain real time reservoir pressure and temperature data, and ensure zonal isolation between the three laterals. The well began producing water after two months of production, but the intelligent completion enabled a comprehensive rate test to be performed on the well using several downhole choke setting combinations. Once rate test data were analyzed, the well's downhole choke settings could be optimized, resulting in a significant improvement in well performance²².

Similarly, many horizontal wells are now candidates for inflow remote control valves and isolation packers strategically placed to:

- Detect and shut off breakthrough of water or gas in a particular segment of the horizontal well.
- Distribute production evenly along the lateral to help provide uniform drainage and recovery.

5 The Intelligent Well Industry

There are approximately 1000 IWCs worldwide located primarily in the deep waters of the Gulf of Mexico, North Sea, and west coast of Africa. During the last few years, Statoil alone has installed more than twenty-five IWCs with over seventy inflow control devices on the Norwegian Continental Shelf.

The principal service companies that build equipment for intelligent completions and provide the services to support the operation of the equipment are:

- Schlumberger
- Halliburton WellDynamics
- Baker Hughes

6 Governmental Regulations and Recommendations

The operator should provide the following information when applying to commingle using an intelligent completion:

- Well name, block, and location with geographical coordinates
- Estimated spud and well completion dates
- A detailed well completion design, including inflow control valves and gauges to be used
- The well completion installation procedure
- Number and description of producing horizons to be produced and commingled, including the depth and thickness of each horizon
- The prospective production rate of each producing horizon
- Reservoir data for each horizon, including where known rock and fluid characteristics, reservoir drive mechanism, bottomhole pressure, productivity index, IPR graph and OOIP (while much of this information will be sketchy for new discoveries, requiring operators to identify what information they have is important to help ensure effective long-term reservoir management in the Gulf of Mexico)
- How the operator will routinely evaluate pressure, temperature and/or production data from the intelligent completion to help optimize oil and gas recovery
- How the operator will allocate production to individual reservoirs for reservoir management and reserves booking purposes¹⁷
- Well management plan, including procedures to handle events such as crossflow and water and gas influx
- Procedures for testing and frequency activation of the inflow control valves
- Reliability information for inflow control valves and gauges to be used
- Contingency plans in case intelligent completion components fail

If deemed necessary, the regulators can meet with the operator to discuss the commingling aspects of the intelligent well completion before approving or disapproving the application.