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1 Practical Commingling Methods and Requirements

The relatively rapid natural decline and relatively low primary recovery factors of many reservoirs in the Gulf of Mexico is leading companies to consider both Improved Oil Recovery (IOR) techniques such as artificial lift and further opportunities for commingling. At present, there are some twelve potential producing horizons in the GOM. Current wells tend to produce those horizons which are more prolific, leaving behind for the time being those of lesser pressures and sizes. While in principle these deferred zones can be produced sequentially later, many may end up not being produced, particularly those with lower reservoir pressures. Drilling wells to produce individual reservoirs in the GOM is expensive, as are dual completions, and companies are not inclined to develop their fields in these manners given the extremely high investment required. In such situation, commingling using intelligent completions and careful monitoring is the logical approach to produce multiple reservoirs.

As previously discussed, key benefits of commingling production from separate reservoirs are:

- Ability to produce hydrocarbon from multiple reservoirs which may not be economic to produce on their own
- Fewer wells and less infrastructure, thus lowering capital expense
- Lower operating expense per BOE produced
- Less environmental impact thanks to fewer locations
- A more sustained production plateau

As mentioned earlier, multiple horizons are being commingled offshore Brazil, Nigeria, the North Sea and the Gulf of Mexico using intelligent well completions (IWC). Producing horizons are separated by seal-bore packers with pass-through connections for control lines and surface control valves/sleeves to regulate the inflow from individual horizons without interference from other producing horizons. All reservoirs are produced simultaneously and efficiently with regard to one another.

Presently, three deep water gas fields in the Gulf of Mexico, Aconcagua, Camden Hills, and King's Peak, are using IWC technology to optimize these subsea developments. The use of IWC equipment to optimize the reservoir is critical to the economic success of these fields. IWC technology enables gas production from multiple zones to be commingled and the well to be reconfigured to shut-off water production without the requirement for well intervention. All zones within each well will have the capability to be commingled initially. As water production occurs, the zones will be shut off as necessary to eliminate water production. IWC technology will thus demonstrate that "real time" reservoir management can significantly improve reservoir performance and enable the subsea developments to be completed and produced economically.[1]

Regulations counter to commingling are often perceived by operators as an impediment to the economic development of low deliverability reservoirs[2]. Even using IWC technology, regulations cannot go away, since designing and operating an IWC to produce multiple reservoirs requires complex engineering and monitoring to ensure the reservoirs produce at rates similar to their individual rates and recover as much oil as possible.

Several parameters govern the reservoirs and must be considered in a commingled completion, for instance:

- The distance between producing reservoirs
- The inflow performance relationship (IPR) curves and productivity indexes (PI) for each reservoir
- The static and flowing bottom-hole pressures of each reservoir
- Fluid properties and water cuts in each reservoir
- The potential size of the completion production tubing

Developing and monitoring an intelligent well system that ensures similar flowing pressures on a depth-adjusted basis from each reservoir will enable effective commingling and enhance production and recovery while preventing crossflow. A composite IPR curve can be estimated as a means to predict the performance of a commingled well in terms of inflow pressures and rates from each zone.

Practical issues associated with commingling recognized by regulators worldwide include multiple inter-related factors:

- Reservoir management and allocation of production to different reservoirs.
- Well integrity, i.e. prevention of cross-flow between reservoirs
- Flow control, including the ability to exclude production of unwanted effluent (water, gas)
- Compatibility of reservoirs fluids

Applications for commingling should address these issues before approval can be granted.

Reservoir management involves ensuring that the IWC can manage production or formation tests from each reservoir independently using the packers and remotely-operated sliding sleeves previously described. Reservoir management requires the ability to monitor pressure at each formation face as well as at the entry to the tubing at each sliding sleeve. Pressure monitoring will enable estimation of production from each reservoir and indicate if sliding sleeves adjustments need to be made to avoid such potential problems as crossflow. Clearly, regulators should require use of these remotely-monitored pressure sensors. Downhole temperature and flow gauges, while usually not essential, can be useful in augmenting the capability to manage the reservoir.

Well integrity refers to zone or reservoir segregation, which is affected by the integrity and reliability of the well mechanical completion. Although IWC technology has a good track record of reliability, the operator should present a clear plan to regulators for what to do if one of the critical elements of the completion fails. Clearly, a production system with a dry tree will facilitate operator intervention if a workover is required to repair a component of an intelligent completion.

Flow control refers to the ability to open or shut off a zone or reservoir in a commingled well at will, an unlimited number of times, without intervention. High level intelligent well systems offer the ability to restrict flow or choke off any particular interval. The ability to shut off zones is important to prevent cross-flow between reservoirs and to exclude production of unwanted effluent (water, gas). The capability to actively and remotely modify the zonal completions and performance through flow control and to monitor the response and performance of the zones through real time down-hole data acquisition is key to maximizing the value and recovery of the field. Effective flow control should be required by regulators.

Compatibility of reservoir fluids refers to the ability of fluids to mix without causing problems such as precipitates or emulsions that will negatively affect the production system.

2 Intelligent Well Elements Relevant to Regulation

The petroleum industry recognizes the definition of an intelligent well completion as one in which control of inflow or injection takes place down hole at the reservoir, with no physical intervention, with or without active monitoring (2001 SPE Forum in St. Maxine, France).

The following elements are required:

2.1 *Flow Control Devices*

Also known as inflow control valves, most flow control devices are based on sliding sleeves or, for bottom reservoir application, ball-valve technologies. These devices are driven by hydraulic, electro-hydraulic or electric systems and can:

- Be binary, i.e. just have on or off positions (not recommended in complex commingling situations)
- Have multiple degrees of opening (“multiple positions”)
- Be infinitely variable/

2.2 *Feed-through Isolation Packers*

To ensure individual zone control and segregation of reservoirs, each zone must be isolated from each other by packers that incorporate feed-through facility for control, communication and power cables.

2.3 *Control Cables*

Current well technology requires one or more conduits to transmit power and data to down-hole monitoring and control devices. These may be hydraulic control lines, electric power and data conductors, or fiber optic lines.

2.4 *Down-hole Sensors*

A variety of down-hole sensors, including quartz crystal pressure and temperature sensors, optical fibers, and down-hole flow meters to monitor flow from each zone of interest, are available and are becoming increasingly reliable. Operators can use redundant systems to increase reliability even further.

2.5 *Data Acquisition and Control*

Surface acquisition systems are required to acquire, validate and store the large volumes of data provided by down-hole sensors. Processing systems are also required to examine and analyze the data to gain insight into the performance of the well and the reservoir. With the knowledge gained from the analysis, predictive models can assist in the generation of process-control decisions to optimize production from a well and asset.

2.6 *Flow Estimation and Flow Allocation*

Flow estimation is the quantification of the mass or volume of fluids from each reservoir in an intelligent well. This is different from flow allocation, which is the division of a total mass or volume measurement of fluids into shares representing the estimated contribution of each reservoir. Given the limited accuracy of multi-phase flow meters, both flow estimation and flow allocation are important in an intelligent commingled well for reservoir management and production accounting. Sound reservoir management requires that every well with two or more commingled reservoirs must have production allocated by reservoir. By collecting reservoir and tubing pressures and, in some cases, downhole flow rates and temperatures, intelligent well completions facilitate allocation of production to each producing horizon.

3 Economic Considerations in Intelligent Well Systems

Intelligent well completions are very expensive due to the high cost inflow control devices, isolation feed-through packers, control cables and lines, and the surface control data gathering systems. The cost of each well completion obviously increases when the well is deeper and has more producing horizons. A current rule of thumb is that each reservoir being isolated requires about half a million dollars in hardware. Rig charges can easily exceed hardware costs, so an intelligent well completion can cost millions of dollars.

In deeper waters of the Gulf of Mexico, where wells often produce at high oil and gas rates, installing and monitoring intelligent well completions is economically justified. The question then becomes what other options should be considered by regulators if an intelligent well completion cannot be economically justified in a low rate commingled well. The following sections discuss two potential options: Oil and Gas Fingerprinting and Production Logging.

4 Oil and Gas Fingerprinting through Geochemistry

Oil and gas “fingerprinting” enables allocation of oil production to individual reservoirs by tracking the geochemical composition of the produced fluid. Produced oil and gas from a particular reservoir bears a distinct fingerprint[8]. Variations in oil and gas composition are understood to be the product of preferential biodegradation of different hydrocarbons based on such variables as temperature, pressure and presence of oxygen, which gives oil and gas from each reservoir a distinct molecular signature or “fingerprint” related to level of degradation. This natural variability in oil and gas composition can be used to allocate oil and gas production along a horizontal well or to assess the contribution of different production streams in a commingled well by mapping the original oil and gas composition distribution (Larter, et al., 2008)[9]. The geochemical procedures such as gas chromatography needed to allocate commingled production within single wells from multiple pay zones have been well documented (Kaufman et al,. 1990)[10]. Of course, fluid samples must be available from each reservoir.

Geochemical techniques for allocating commingled production from multiple zones in a single well are accurate, rapid and relatively inexpensive and do not interrupt production. The procedure is applicable to vertical, deviated and horizontal wells whether producing naturally or through artificial lift, and zonal performance problems can be detected at any time during the life of the well.

4.1 *Case Studies*

A gas field in Oman produces from three rich gas-condensate bearing sandstone reservoirs. To date, there are twenty-three development wells of which eleven are on production. Only three wells commingle from the three reservoirs, and one well commingles only from the upper two reservoirs. The common allocation methods previously used involved zonal isolation and were limited because the commingled flow rates obtained on the surface were not necessarily representative of isolated formation flow rates. Geochemical techniques using gas chromatography and isotope analysis enabled properly allocating gas production from commingled reservoirs[12].

In the super-giant Burgan field in Kuwait, approximately 50 oils were analyzed to enable application of reservoir geochemistry in the field to help address the following reservoir characterization and management issues:

- Reservoir continuity
  - The Burgan field contains five major producing horizons. Each of these is further subdivided into several reservoir layers. Oil fingerprinting along with other oil field data are used to evaluate vertical and lateral compartmentalization in the field.
- Production allocation and well diagnostics
  - The relative proportions of individual oils in an oil mixture can be determined with GC, providing a rapid means of production allocation without taking wells off production. This method was also applied in the Burgan field to evaluate the extent of oil mixing in the well-bore due to mechanical problems, or in the reservoir because of cross-flow from deeper, higher-pressure reservoirs.
  - Although the oils in the Burgan field are compositionally very similar, the minor differences are sufficient to monitor oil from different reservoirs and field compartments.

5 Production Logging

Production logging is a means of measuring the quantity of oil and/or gas being produced from a specific reservoir using such technology as wireline spinner surveys; however, production logging has accuracy limitations and can only indicate relative flow at the point in time when the survey is run. Reservoir testing and other analytical work are often needed to support the results of production logging and enable reasonable production allocations between reservoirs. Moreover, in a subsea (dry tree) completion, running production logs would be a highly expensive proposition in that a mobile rig would be required.

6 Application of Oil and Gas Fingerprinting and Production Logging to Commingling Regulation

If a well has a properly functioning intelligent completion, oil fingerprinting and production logging are unnecessary; however, situations may arise in shallow, depleted offshore fields where an operator demonstrates that the cost of an intelligent completion renders commingling uneconomic. In these situations, it is advisable for regulators to require the following stipulations before approving commingling:

- The operator provides evidence that the cost of an intelligent completion would render commingling uneconomic
- The operator provides evidence that the depth-adjusted static pressures in the reservoirs to be commingled are within 100 psi.
- Hydrocarbon fingerprinting or production logging is carried out at least once every quarter. If hydrocarbon fingerprinting or production logging provide evidence of cross-flow or other downhole problems, the operator will immediately take steps to work over the well to remedy the problem.