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Cost-Effective Life-Cycle Profile Control Completion System for Horizontal and Multilateral Wells

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Abstract

A new cost effective life-cycle profile control completion system has been developed to solve major problems associated with surveillance and interventions in horizontal and TAML level 2 multilateral wells completed with ESP.

As fields age and produced water oil ratio increase, surveillance and profile control in the multilateral wells drilled in PDO have become a major challenge. These wells are TAML level 2 multilaterals. Production from two to nine barefoot lateral legs is commingled and artificially lifted by electrical submersible pumps (ESP). ESPs prevent through tubing access to the laterals. Installation of a Y-tool allows for wireline (WL) or coiled tubing (CT) deployed logging and some remedial CT intervention. Well and reservoir management challenges arise from completion design limitations such as barefoot completion, commingled production, the presence of ESPs, access to the TD of the backbone and inability to selectively re-enter the laterals.

New minimum-cost zonal isolation and downhole control technologies provide an opportunity to retrofit TAML level 2 multilateral wells for well and reservoir management purposes. Swelling elastomers in the form of the expandable zonal inflow profiler (EZIP) tool allows segmentation of wellbore section into a discrete number of management intervals. Interval control valves provide the capability to shut-off water or gas.

This paper describes the design and application of remotely operated selective EZIP completion technology (SECTOR) in TAML Level 2 multilateral wells in the carbonate reservoirs of Qarn Alam Asset of PDO. With SECTOR, existing TAML Level 2 multilateral oil producers are converted to TAML-5 multilateral wells. The lateral legs are isolated from

each other and can be selectively produced, shut-off or stimulated. The need for CT interventions for production logging and water shut-offs is removed. The water shut-off process offered by this technology is reversible.

Introduction

Multilateral wells have been adopted by operators worldwide to increase production per well and to lower unit technical costs of projects^{1, 2, 3}. Three oil fields in the Qarn Alam Cluster of Petroleum Development Oman's concession area in North Oman have been developed in patterns of horizontal and multilateral oil producers underlain by corresponding water injectors.

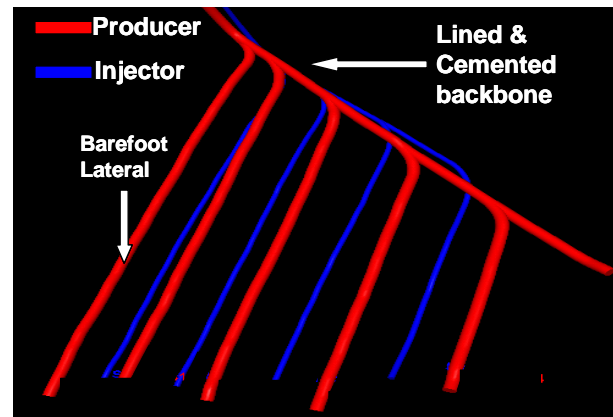


Figure 1: Typical Injector Producer pair showing multilateral oil producer underlain by a multilateral water injector.

Some 130 single horizontal and TAML level 2 multilateral wells have been drilled in the fields as follows:

Field	GL	ESP	WI	TOTAL
X	0	16	10	26
Y	0	12	6	18
Z	17	43	26	86
TOTAL	17	71	42	130

The horizontal wells are completed barefoot while the multilateral mother bore are cased off with a 7" cemented liner and provide backbone and exit windows for the 6 1/8" laterals that are completed barefoot. Injection or production from those laterals is commingled. Due to low reservoir pressure and high water cut, the wells cannot support natural flow and have to be artificially lifted. Most of the horizontal oil producers are gas lifted (GL). Most of the multilateral

oil producers are completed with ESP as shown in figure 2. This makes through tubing intervention impossible, except when a Y-tool is used, which allows coiled tubing deployed logging and water shut-off.

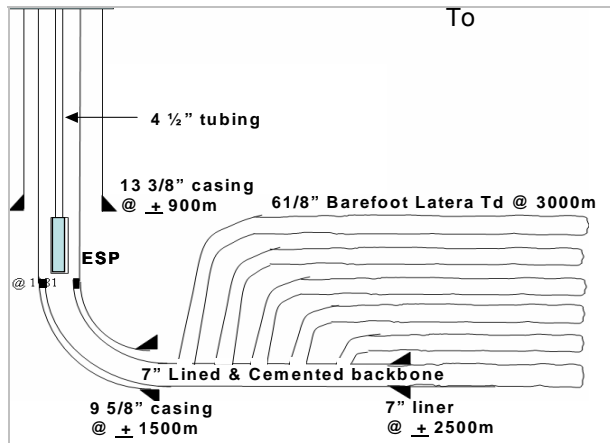


Figure 2: Schematics of a typical TAML LEVEL 2 multilateral oil producer

Recently, the industry has been adopting an integrated smart fields approach to optimize hydrocarbon recovery⁴. A key success factor for managing a water flood project in a fractured carbonate reservoir is conformance control and how much of the water injected actually contributes to sweep and ultimate recovery. This makes effective surveillance for inflow profiling and water shut off (WSO) interventions key business activities in the management of water floods to maximize the hydrocarbon resource lifecycle value.

Surveillance and profile control in these TAML level 2 multilateral wells completed with ESPs have been a major challenge. This is because the laterals and window exists have not been configured for selective re-entry and zonal isolation. Current attempts to manage such wells involve a four-stage sequential re-entry program:

1. Retrofit a Y-tool
2. Logging operation to determine fluid inflow profile. If this log data is successfully acquired, then
3. Retrieve Y-tool and perform water shut-off
4. Post operation logging if necessary. A Y-tool would be utilized again.

Apart from being expensive, the probability of success is hardly better than 50%, and takes up to one year to plan and execute, with significant production deferment.

Life Cycle Solution Concepts

In carbonate reservoirs horizontal wells and legs of multilateral wells have been completed barefoot. In clastic reservoirs stand-alone wire-wrap screens have been used. Such completion designs create the following challenges:

- Inability to control unwanted water in horizontal wells with stand-alone wire-wrap screens.
- Inability to detect the inflow profile in beam pump wells.

- Inability to control unwanted water & gas in wells with horizontal open completions.
- Difficult access to control unwanted water in ESP-completed multilateral wells.

Surveillance and profile control capabilities have become a key building block for well and reservoir management in maturing fields with increasing production of unwanted water. To overcome the limitations of past completion practices swelling elastomers in the form of expandable zonal inflow profiler (EZIP) are applied to segment the wellbore into a discrete number of management intervals. Different of operating models for segmented wells are pursued:

Lower CAPEX – Higher OPEX operating model

In an onshore low-cost operating environment the fields may be developed with a large number of horizontal wells that are artificially lifted with beam pumps. The horizontal wellbore sections are segmented with EZIP and wire-wrap screens to create a certain number of flow segments. In the case that a water-producing feature is identified in the drilling phase water shut-off in the completion phase is carried out by using standard casing. This practice minimizes incremental capital expenditure (CAPEX) but provides the capability to shut-off unwanted flow segments at a later stage. Dual completions have been introduced to allow logging while pumping in beam-pump wells. Unwanted flow segments are shut-off with patches, plugs or by chemical means. Surveillance and shut-off operations require coiled tubing units and well pulling hoists. Operating a large number of wells requires an adequate well services capability.

Medium CAPEX – medium OPEX operating model

This way of operating segmented horizontal wells requires a higher CAPEX for initial completion in the form of sliding side doors (SSDs)⁵. It has been adapted to segment existing barefoot horizontal oil producers with liners featuring EZIP for zonal isolation and SSDs for profile control. Those wells have been gas-lifted. When an intervention becomes necessary, memory-PLT is first run to identify the unwanted flow segment and a coiled-tubing deployed shifting tool is then run to close an SSD. In this way a segment shut-off is reversible. This operating model becomes unfavourable in the case of a frequent requirement for mobilizing coiled tubing units to shift SSD's.

Higher CAPEX – Lower OPEX Operating Model

A higher upfront investment in completion equipment can solve the challenges associated with surveillance and interventions in horizontal and multilateral wells. This approach is pursued to recomplete horizontal and multilateral ESP produces to minimize further interventions for production optimisation. The completion design allows monitoring and control of wellbore segment horizontal sections or legs of multilaterals from surface. The incremental capital

expenditure for interval control valves, control lines and surface control units would be offset with lower operating cost. With this completion, surveillance and shut-off activities do not require well entries.

Surveillance and water shut-off in TAML Level 2 multilateral wells

Fractures cause shortcutting between water injectors and oil producers. The consequence of shortcutting is high water cuts: The three fields produce at average water cuts of 91% in Z, 68% in Y and 82% in X. The water short-circuits lead to ineffective voidage replacement and loss of reservoir pressure. The mobility of water keeps oil from flowing into the wellbore, effectively decommissioning the entire well once water breaks through one of the laterals. In addition, a high water cut limits tubing potential and negatively affects the vertical lift efficiency. In the case of high water cuts surveillance and intervention activities for pattern optimization through profile control are required. However, the inherent limitations of the well design shown in figure 1 have created the following challenges:

Surveillance

- Lack of through bore access due to ESP,
- Requirement of a Y-tool to enable through tubing interventions.
- Limited CT reach in the horizontal due to buckling and obstructions.
- Challenge to enter the right lateral with a logging tool or intervention BHA.
- Uncertainty to identify point of water ingress due to challenges associated with PLT data interpretation.

Surveillance poses a challenge for planning and executing a series of well services activities:

First, a hoist needs to be mobilized to install a Y-tool on the ESP completion strings to allow CT access. This has generally been deferred to when the ESP fails. Then, a coiled tubing unit needs to be mobilized for CT deployed production logging.

Water shut-off

In the case of successful surveillance activities a decision can be taken to carry out water shut-off either inside a lateral or to completely shut off the offensive lateral from the mother bore. The main limitations and challenges encountered are:

- The risk of not being able to run casing patches and expandable tubulars to target setting depth due to doglegs and window exits.
- The risk of not being able to create an annular seal in a corroded backbone with a packer.
- The risk of not being able to place chemicals in the right place to shut-off water.
- The difficulty of reversing shut-off if it proves sub optimal.

Current practices of water shut off in the laterals and horizontal sections have been costly, have had mixed

success, and have been accompanied by both visible and invisible unscheduled deferment.

Mechanical methods of profile control have been tried in many water injectors and one producer with a success rate of less than 60% due to lack of sealing of the packer against the mother bore liner, or due to corrosion, scale, packer element failure, or premature corrosion of the straddle pipe.

Chemical methods of profile control have been tried in both water injectors and oil producers with mixed success. The success rate has been less than 50% due to poor identification of the location of water ingress, hydrodynamic connectivity, incorrect choice or chemicals and as well as incorrect placement.

IMPROVEMENT OPTIONS

Retrofit wells with 3½" liner with sliding side doors

Existing multilateral wells can be segmented with EZIP in the same way as it has been done for existing barefoot horizontal gas lift producers (*medium CAPEX – medium OPEX model*). As coiled tubing access is required to shutting off unwanted flow segments by closing sliding side doors this option is unfavorable in ESP completed wells. The decision on which flow segment to close or to produce still requires sequential multiple entries for production logging, coiled tubing operations and possibly hoist re-entry, if coiled tubing operations fail.

Retrofit wells with smart well technology

Application of smart well technology has been growing in the Industry with an increasing number of applications in maturing fields and carbonate reservoirs^{6, 7, 8}.

In the Qarn Alam cluster of PDO, one multilateral oil producer with 6 lateral legs was retrofitted with smart well technology in 2002 (*high CAPEX - high OPEX model*). Water producing legs were identified through selective production testing. This trial proved that profile control could deliver more oil and less water from existing TAML level 2 multilateral wells⁹. However, high capital expenditure and as well as the requirement to callout the smart well technology provider to just operate the interval control valves prevented further deployment.

New multilateral well completion for minimum interventions

A new completion concept was developed to meet the following well operating requirements:

- Reduce the time needed for surveillance, data gathering, analyzing well performance, and intervention planning and profile modification.
- Allow for real time surveillance on each lateral
- Detection of unwanted flow segment without the need for production logging.
- Eliminate need for coiled tubing interventions to shut-off or re-open any flow segment or lateral.
- Flexibility to produce or shut off any lateral at any time from surface.

The driver was to optimize the value of hydrocarbon assets by reducing capital expenditure and operating expenditure through design simplification, elimination and replacement of smart well technology components, elimination of the need for coiled tubing interventions and reduction of deferment by faster response to adverse well conditions.

This new completion concept is called **Remotely Operated Selective EZIP Completion Technology** or SECTOR. SECTOR is a minimum-cost intelligent completion solution utilizing swelling elastomers for wellbore segmentation and on-off interval control valves for profile control. Control lines are embedded in the water and oil swelling elastomer seals of the expandable zonal inflow profiler tool. The advantages of SECTOR are as follows:

- Easy to install zonal isolation technique. Elastomers swell in contact with either produced water or oil to create a closed annulus completions.
- Reversible segment shut-off from surface.
- Improved POS for chemical water-shut-off due to higher chance of correct placement.
- Eliminates further well services activities, i.e. production logging and water shut-off.
- Ability to integrate with downhole monitoring technology, i.e. distributed temperature sensing.

Swelling elastomers is an emerging technology that is increasingly applied in Shell for zonal isolation as an alternative to cement^{10,11}. The expandable zonal inflow profiler (EZIP) tool is a conventional joint of casing coated with a discrete number of bands made of elastomers that swell in contact with produced well fluids^{12, 13}. By swelling against the formation the annulus is closed and the seal is self-energized. Typical operating envelopes for diffusion and osmotic process have been 50-80°C and 5 to 90 days swelling time depending on properties of the formation fluid. EZIP brings the benefits of:

- A “rubber-on-pipe” commodity product instead of specialty engineered packers,
- Simple deployment process as no mechanical or hydraulic manipulation is required to create an annular seal.
- Flexibility to modification to suite variety of purposes. EZIP-CL™ is an EZIP product line with fitted control lines.

For the initial wells SECTOR has been designed in the following way:

- Each lateral in the mother-bore is straddled with two EZIPs on either side of the window exit.
- One interval control valve (ICV) is placed between two EZIPs.
- The completion is deployed on 3 ½" tubing inside 7" liner and crossed over to 7" tubing to surface once inside 9 5/8" casing.

- The ICV is operated by direct hydraulics from surface via ¼ inch control lines encased in a flat-pack. The ESP is installed inside the 7" tubing. In the event of failure, the ESP can be pulled and replaced normally without disturbing the SECTOR assembly. (Fig 3).
- The components are made of corrosion resistant materials to meet requirements for mild H₂S and CO₂ corrosion.
- A down-hole wet-connect has been eliminated from the completion to improve reliability and reduce cost.
- The system utilizes a mobile manual surface control system. It allows the operator's staff to open or close an ICV. As a minimum, only one surface control unit is required for the whole field. An automated unit that will enable the ICVs in the field be operated from one common base is available and may be implemented at a later stage.

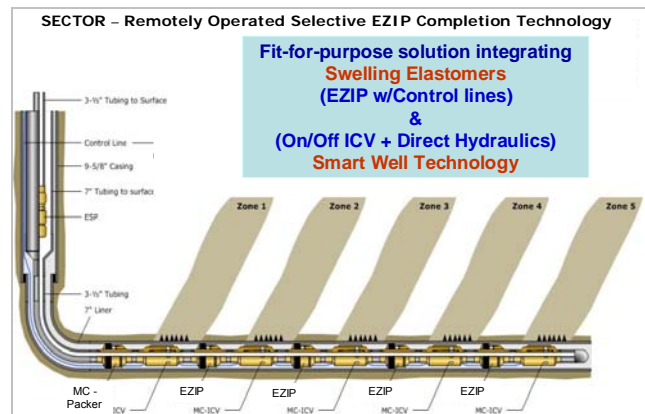


Figure 3: Schematics of SECTOR completion designed for retrofitting a TAML LEVEL 2 multilateral producer with 6 laterals.

For a multilateral well with n laterals, the down-hole components of a SECTOR completion will include the following:

- One production packer.
- n – 1 EZIP-CL tools (CL = control line). The liner comprises 3 ½" base pipe, n+1 pieces of ¼" control line, and 5 straps each of oil and water swellable elastomer seals alternately vulcanized on the pipe (Fig. 6).
- n ON/Off ICV placed between two EZIP-CL packers straddling a lateral junction.
- Two splice subs are integrated per EZIP joint to protect leak proof connections of the control lines.
- Flat packed n + 1 control lines to control the n valves.



Figure 4: Expandable zonal isolation profiler tool with feed-through capability for control liners.

Candidate Selection

Well performance is regularly reviewed by an integrated Petroleum Engineering team. Multilateral wells that have higher than expected water oil ratios and lower than expected decline in Oil rate are candidates for water shut off. The probability of having to repeat the water shut off cycle in each well is assessed based on the number of legs in each multilateral and position of the well in the reservoir relative to the aquifer and water injectors. Wells that may require water shut-off in at least two legs (have minimum 4 legs) are potential candidates for SECTOR. These candidates are then firmed up based on the following criteria.

- Presence of external zonal isolation – Cement
- Presence of internal hydraulic isolation – Corrosion
- Ability to run SECTOR to desired depth – Wellbore profile

For SECTOR to work there must be zonal hydraulic isolation between laterals. This is assessed by evaluating the quality of cement between each lateral window (behind the 7" liner). There should also be internal isolation between the ICVs. This is dependent on the status of the casing and where the EZIPs are placed. These are confirmed by first performing a drift run to TD with a 6-1/8" bit and a dummy BHA that should in principle be harder to get to TD than the SECTOR assembly. Then a CBL/VLD and USIT in cement and corrosion mode are acquired to firm up candidates.

Installation procedure

Retrofitting existing ESP completed wells with a SECTOR completion is carried out with a well pulling hoist. In a typical TAML level 2 multilateral producer having 9 5/8" production casing, 7" production liner and 5 laterals, commingled and artificially lifted with ESP, the basic installation procedure is as follows:

- I. Retrieve existing ESP completion.
- II. Make a clean out trip with a dummy bottom hole assembly to ensure the completion can be run to target TD in the horizontal mother bore without obstructions.
- III. Make up and RIH SECTOR completion consisting of: Bull plug - 5 ICVs already made up to an EZIP

joint at completion workshop - Production packer with 6 feed through ports - 3/2" tubing to top of 7" liner crossed over to 7" tubing to surface. The flat-packed control lines should be strapped and fastened securely during this deployment.

- IV. Land completion with 7" hanger on a wellhead that has been modified to cater for penetrations for 6 – 8 control lines.
- V. Set production packer.
- VI. Re install ESP pump on desired tubing.
- VII. Open all ICVs, start up ESP and bring well on production.
- VIII. Allow required time for EZIP to swell and isolate lateral windows and Operate ICV as desired using surface hydraulic unit.

Installation risks and mitigation

Installation risks were identified and mitigation plans were put in place.

Inability to run SECTOR to target setting depth

This can happen if the wellbore drag exceeds the set down weight that is applied on the bottom hole assembly (BHA). Alternatively, the BHA may get held up at the window exits or the EZIPs swell beyond the liner/casing internal diameter prior during running the completion. Torque and drag modeling is carried out to clarify if the SECTOR completion can be run to target depth in a particular well. The EZIP joints are actually friction reducers as they provide additional stand off of the string from the wellbore. Clean out trips using a dummy assembly have been successfully executed on 5 well workover candidates. A number of properly designed BHAs have been run across the windows in these ML. The orientations of the windows as well as the dogleg severity were also modeled to give an indication of the possibility of any hold ups. The swelling time of the oil and water elastomers were engineered to be at least 200% of the time required to deploy completion assembly to depth.

Inadequate isolation of the lateral windows by cement or corroded mother bore.

Well re-entry history indicates that production liners in some mother bore suffered various degree of corrosion that can be largely attributed to liner erosion due to pipe rotation by rig or hoist within the liner. While this occurrence is not widespread, there is the risk that if the liner on the mother bore is corroded or if there is inadequate isolation of the lateral exit windows by cement, it will be impossible to independently produce or effectively shut off the laterals. Prior to deploying the SECTOR completion and during the dummy drift run, ultrasonic image logs (USIT) and cement bond logs (CBL) were acquired and used to evaluate corrosion and zonal isolation between the legs. Figure 5 shows the log example of a candidate well, which was dropped due to poor isolation between the laterals, and figure 6 shows another candidate with good isolation between the windows respectively. Only ML wells with good isolation between the windows were selected as candidate for the trials. Internally corroded mother bore liner backbone was not an

issue, as the EZIPs will compliantly swell to the configuration of the casing.

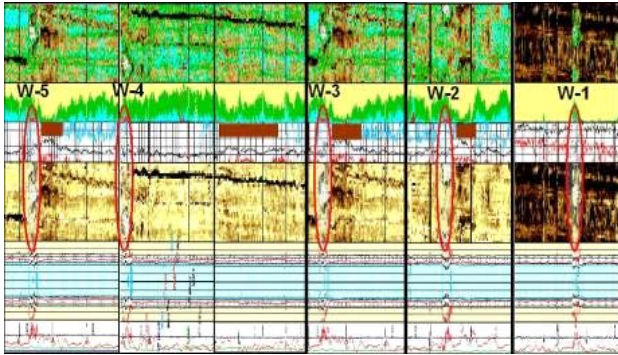


Figure 5: USIT and CBL logs showing poor isolation between window exits 2 through 5.

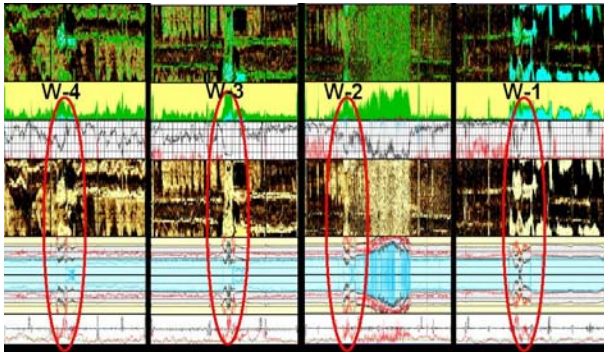


Figure 6: USIT and CBL logs showing good isolation between windows 1 through 4.

Corrosion

The corrosion of the SECTOR completion components will result in a failure of whole system. The completion will be extremely difficult or impossible to retrieve once the EZIP seals are swollen and the seals are energized against the liner. Consequently only completion materials rated to ASTM 4140 that meets corrosion resistance requirements (mild H₂S, CO₂), during the remaining life of the well is used. Nonetheless, a corrosion study will be undertaken to determine material specification for deployment beyond the initial phase.

Oversized ESP

Closing one or more laterals will reduce the well PI and make the ESP become oversized for the remaining legs. All ESPs for a SECTOR completion will be run with variable speed drive (VSD) which can extend the recommended operating range (ROR) of the pump from the lower ranges of 300 m³/d expected for MLs with only two legs open to the upper range of up to 1800 m³/d expected from MLs with six legs or more open.

No more access into laterals

This risk was consciously accepted. TAML level 2 ML wells are not designed for easy entry and past attempts at lateral reentry have been expensive with

limited success. The converse of this risk is that SECTOR will facilitate a successful and selective bullheading of chemicals into a selected leg as well as allow gathering of led specific data such as flow rate, pressure, temperature, water-oil-ratio and PI.

DEPLOYMENT PLAN

Screening and economic evaluation indicates that a life cycle profile control completion system such as SECTOR becomes cost efficient in multilateral wells with a reasonable probability that a production log and subsequently water shut off will be required at least twice during the remaining life of the well. Hence most existing multilateral wells in PDO are candidates for this technology. The technology will be deployed in a staircase manner starting initially with retrofitting five wells having more than 4 laterals each with SECTOR. The learning from these initial 5 wells will be used to extend the technology to the whole spectrum of multilateral wells in PDO (Fig.7). SECTOR completions can be extended to ML water injectors where the need to control the injection profile into each leg is identified. Water injection profile can be controlled by sequential injection into each leg through on/off ICVs or by continuous injection through variable ICVs. SECTOR design is flexible and can be modified for any ML between two to nine legs. Each additional leg requires only an additional joint of EZIP and one ICV.

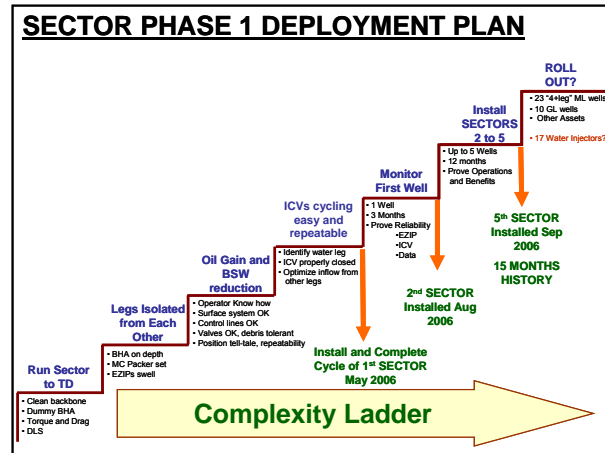


Fig. 7 Deployment plan for SECTOR in Qarn Alam Asset

CONCLUSION:

A new multilateral well completion for minimum intervention has been developed that solves the problems associated with surveillance and interventions in ESP completed TAML level 2 multilateral wells.

Remotely Operated Selective EZIP Completion Technology, (SECTOR), integrates swelling elastomers for zonal isolation, minimum-cost interval control valves for profile control, direct hydraulics to open or close the ICVs. SECTOR completions are implemented to optimize production in fractured carbonate reservoirs through profile control. Five wells have been selected for the first phase of installation to prove the concept. Successful completion of phase 1 will lead to a wider scale deployment of SECTOR technology within PDO following the operator's

technology deployment model¹⁴. SECTOR provides greater flexibility to manage wells for water flood optimization. The results and evaluation of SECTOR will be subject of follow-up papers.

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