Aramco uses swell packers to enable smart open-hole, multilateral completions for EOR

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SAUDI ARAMCO HAS successfully used both horizontal and MRC wells (multilateral with greater than 8 km of reservoir contact) to enhance and maximize hydrocarbon recovery from its reservoirs. In recent years, the integration of both intelligent and passive inflow control completion systems have further enhanced the value of MRC well by providing inflow control, better inflow profiles, and downhole monitoring capabilities.

Saudi Aramco's first intelligent well completions were drilled as 7-in. fullbore wells. A cemented 7-in. liner was placed below the conventional 9 5/8-in. casing, providing lateral isolation and a means to conventionally drill the TAML level two multilateral wells. Standard 3 ½-in. ICVs and mechanical packers were used to provide the required intelligent well completion (Figure 1).

This completion type proved very successful and is utilized in many of Aramco fields as required to provide intelligent well control for MRC wells. Following this success, Saudi Aramco partnered with two service companies to develop an open-hole version of this completion utilizing swelling packers for lateral isolation.

This would save the cost of the 7-in. liner and associated rig days and reduce the possibility of control-line leaks as the use of pass-through packers would minimize the use of control-line splices in the new design. The upfront lab testing for the swell packers and the first successful implementation for the open-hole version of the MRC intelligent well in Aramco will be discussed.

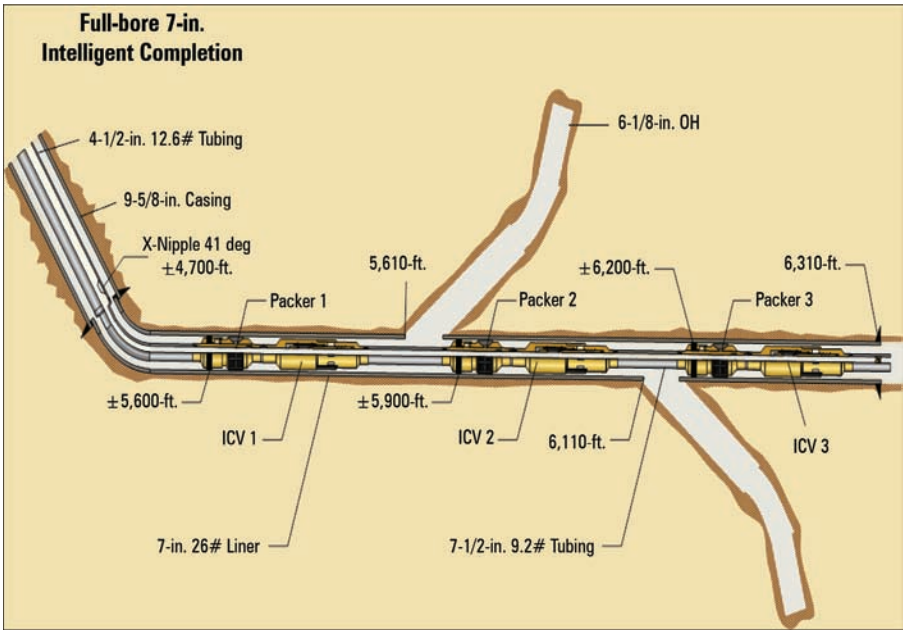


Figure 1: Saudi Aramco's first intelligent well completions were 7-in. fullbore wells. TAML level 2 multilaterals were drilled, with 3 ½-in. ICVs and mechanical packers.

LABORATORY TESTING

Prior to the field trial installation of the open-hole smart well field trial in Shayba, a laboratory test was carried out in conjunction with Saudi Aramco to verify the swelling and sealing ability of Swell Packer with crude oil samples with a range of viscosities from different oil fields. The test was carried out at Saudi Aramco's research and development facilities in Dhahran. The three main objectives were to verify the swell packers performance in Saudi Aramco crude oils with respect to:

- Swelling (verify swelling of swelling packer in different crude oils).
- Sealing capacity (swelling packer ability to withstand DP after swelling).
- Expansion rate (time for the rubber element to seal and hold DP).

For the test, 1:5 scaled packers were utilized for ease of handling in the laboratory (Figure 2). Both separator crude oils and bottomhole samples where used for the test. Table 1 contains the reservoir data that were used as basis for the test.

The numbers in the brackets are dimensions for the 1:5 scale test swell packers.

Reservoir pressure and temperature were applied to the test autoclave during the swelling period in order to simulate downhole conditions. The pressure was increased at a pre-determined interval of 50 psi until a leakage occurred. The final pressure tests are listed in Table 2.

For the Zuluf "live" sample, the test was terminated before maximum pressure was achieved, resulting in a maximum differential pressure of 1,117-psi DP. The reason for terminating the test was due to gas evolving in the autoclave during filling, which resulted in a non-representative test.

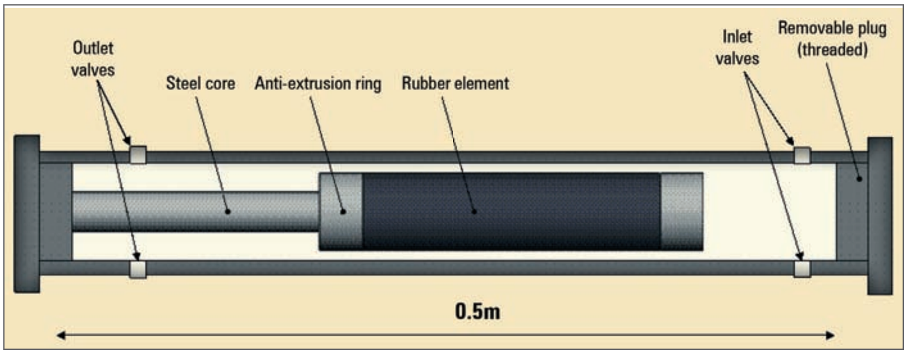


Figure 2: A lab test to verify swelling, sealing and expansion rate indicated that the packers could provide an annular seal for the Shayba open-hole smart wells.

As there were a number of differential pressure tests in a given interval, it was possible to determine the swelling time of the different hole dimensions and crude oils. Viscosity is one of the major factors that influence the swelling process. Results from the 1:5 scaled tests can be found in Figure 3. Figure 3 also details the swelling profiles against time for the range of swell packer sizes from the 1:5 scaled test for the following dimensions:

- 3.5-in. base pipe, 5.8-in. OD swell packer for 6 1/8-in. hole ID
- 4.5-in. base pipe, 5.8-in. OD swell packer for 6 1/8-in. hole ID
- 7-in. base pipe, 8.2-in. OD swell packer for 8.5-in. hole ID

In conclusion, the results from the laboratory test verified swelling and sealing of swell packer for the range of crude samples provided, the maximum differential pressure of swelling packer exceeded the required DP, and the expected sealing time was confirmed. The positive result confirmed that the swelling packers would be able to provide an annular seal for the Shayba open-hole smart wells.

COMPLETION DESIGN

The use of swelling packers for zonal isolation offers a number of advantages over conventional completion techniques. The 7-in. liner can be replaced by a 6 1/8-in. open-hole section while still allowing the operator to install 3 ½-in. interval control valves.

This slimming of the wellbore continues all the way to surface, delivering both significant savings in time and cost. The cable feed-though feature of the swell packers removes the need to splice the control lines for the interval control valves and monitoring devices, reducing rig time to run the completion and removing potential failure points as cable splices are not required.

The open-hole smart well completions design with swell packers enable the inflow from different reservoir sections to be remotely monitored and controlled from the surface without any well intervention. The smart well completion consisted of four sub-assemblies:

1. Swell packer and interval control valve for the motherbore.
2. Swell packer and interval control valve for lateral 1.
3. Swell packer and interval control valve for lateral 2.
4. Pressure temperature sensor and production packer in the 7-in. liner.

Field	Field Type	Open hole size [in]	Base pipe size [in]	Required differential pressure [psi]	Reservoir pressure [psi]	Reservoir temperature
Shayba	Oil	6 1/8 [1.23]	3 1/2 [0.7]	1000	2475	195 °F
HRDH	Oil	6 1/8 [1.23]	4 1/2 [0.9]	500	2700	195 °F
HWTH	Oil	6 1/8 [1.23]	4 1/2 [0.9]	500	2700	160-180 °F
SFNY	Oil	6 1/8 [1.23]	4 1/2 [0.9]	500	2700	160-180 °F
SFNY	Oil	8 1/2 [1.23]	7 [1.4]	500	2700	160-180 °F
MRJN	Oil	6 1/8 [1.70]	4 1/2 [0.9]	500	2700	160-180 °F
MRJN	Oil	8 1/2 [1.70]	7 [1.4]	500	2700	160-180 °F
Zuluf	Oil	6 1/8 [1.23]	4 1/2 [0.9]	500	2700	160-180 °F
Zuluf	Oil	8 1/2 [1.70]	7 [1.4]	500	2700	160-180 °F
Zuluf "live"	Oil	6 1/8 [1.23]	4 1/2 [0.9]	500	2700	160-180 °F
SFNY "live"	Oil	8 1/2 [1.70]	7 [1.4]	500	2700	160-180 °F

Table 1 (above): Reservoir data used as basis for the laboratory test. Numbers in brackets are actual dimensions for the test, which was scaled 1:5.

Table 2: Pressure in the test was increased in steps of 50 psi until leakage occurred.

Field	Field Type	Open hole size [in]	Base pipe size [in]	Reservoir pressure [psi]	Required differential pressure [psi]	Tested differential pressure [psi]	Safety factor [tested DP/required DP]
Shayba	Oil	6 ? [1.23]	3 1/2 [0.7]	2475	1000	2790	2.9
HRDH	Oil	6 ? [1.23]	4 1/2 [0.9]	2700	500	2848	5.7
HWTH	Oil	6 ? [1.23]	4 1/2 [0.9]	2700	500	2755	5.5
SFNY	Oil	6 ? [1.23]	4 1/2 [0.9]	2700	500	2602	5.2
SFNY	Oil	8 1/2 [1.23]	7 [1.4]	2700	500	3397	6.8
MRJN	Oil	6 ? [1.70]	4 1/2 [0.9]	2700	500	3181	6.4
MRJN	Oil	8 1/2 [1.70]	7 [1.4]	2700	500	2891	5.8
Zuluf	Oil	6 ? [1.23]	4 1/2 [0.9]	2700	500	2891	5.8
Zuluf	Oil	8 1/2 [1.70]	7 [1.4]	2700	500	3325	6.7
Zuluf "live"	Oil	6 ? [1.23]	4 1/2 [0.9]	2700	500	1117	
SFNY "live"	Oil	8 1/2 [1.70]	7 [1.4]	2700	500	3263	6.5

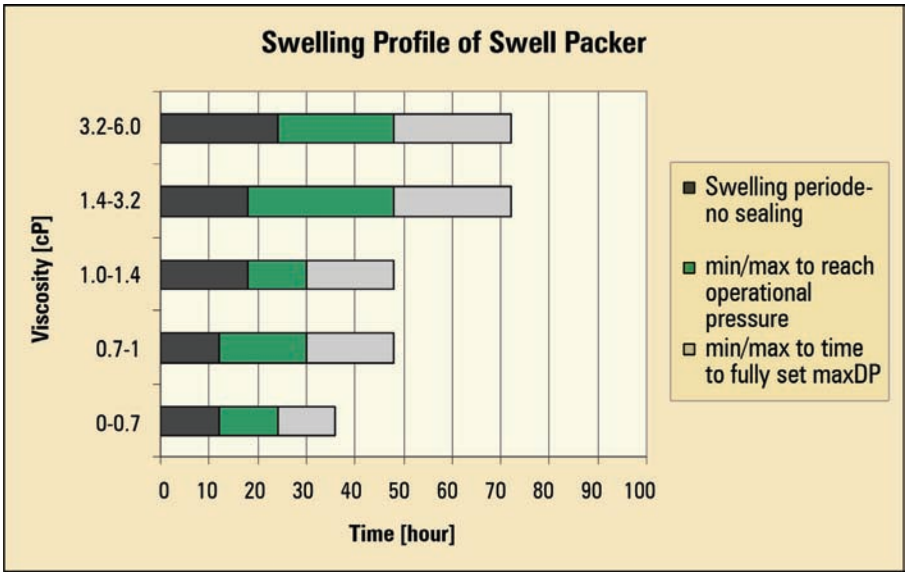
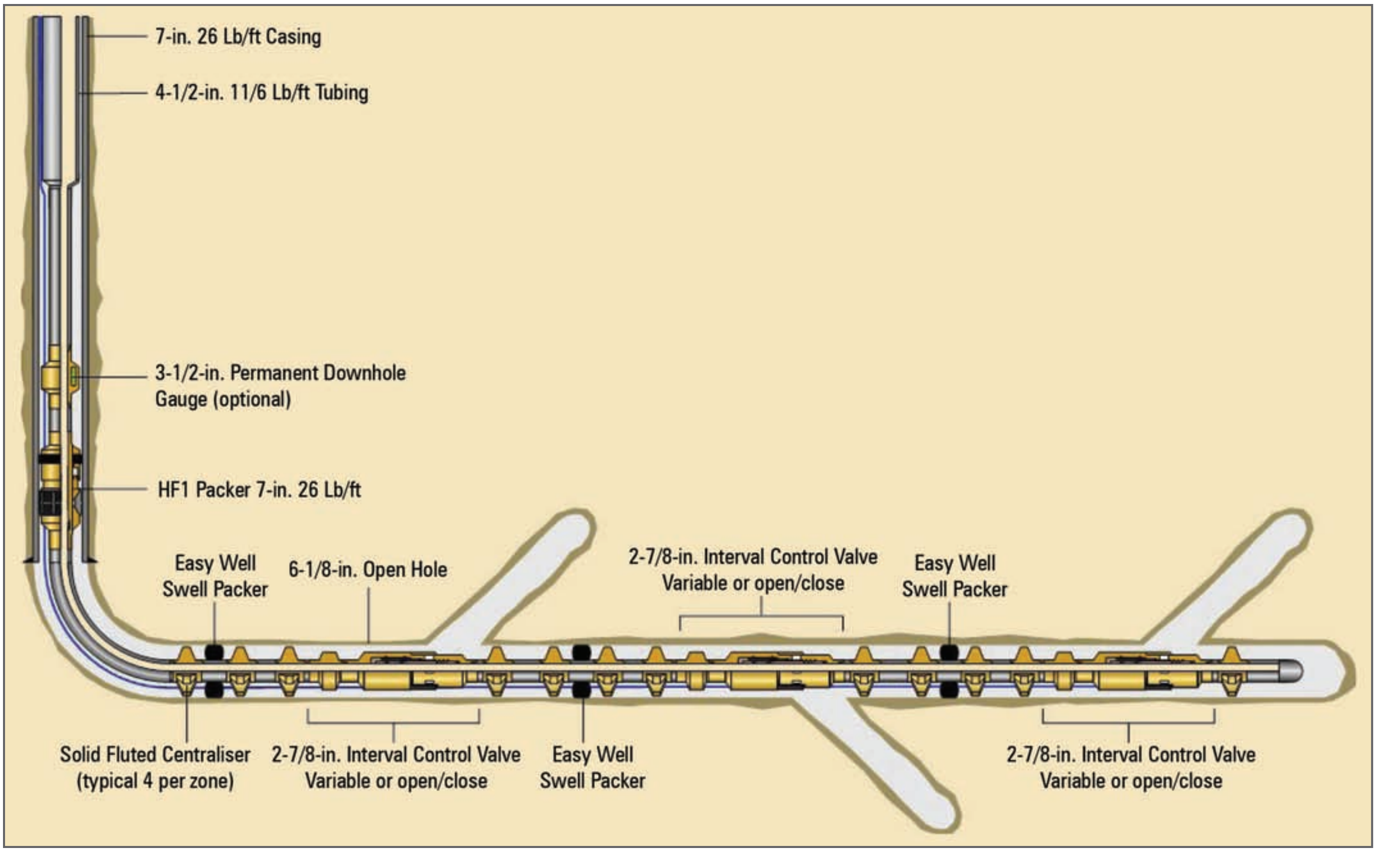


Figure 3: Swelling profiles for various dimensions of swell packers.

Figure 4 shows the proposed cross-section of the well and the location of the completion equipment in the wellbore.

The interval control valves (ICV) utilized for this completion have 10-Position flow trim operated using the accupulse choking system. The flow ports were sized so as to provide inflow control under different flow conditions. On the 3 ½-in. valves, the flow area varies from 0.141 sq in. for position-1 to 6.9 sq in. while fully open. The valves use a tungsten



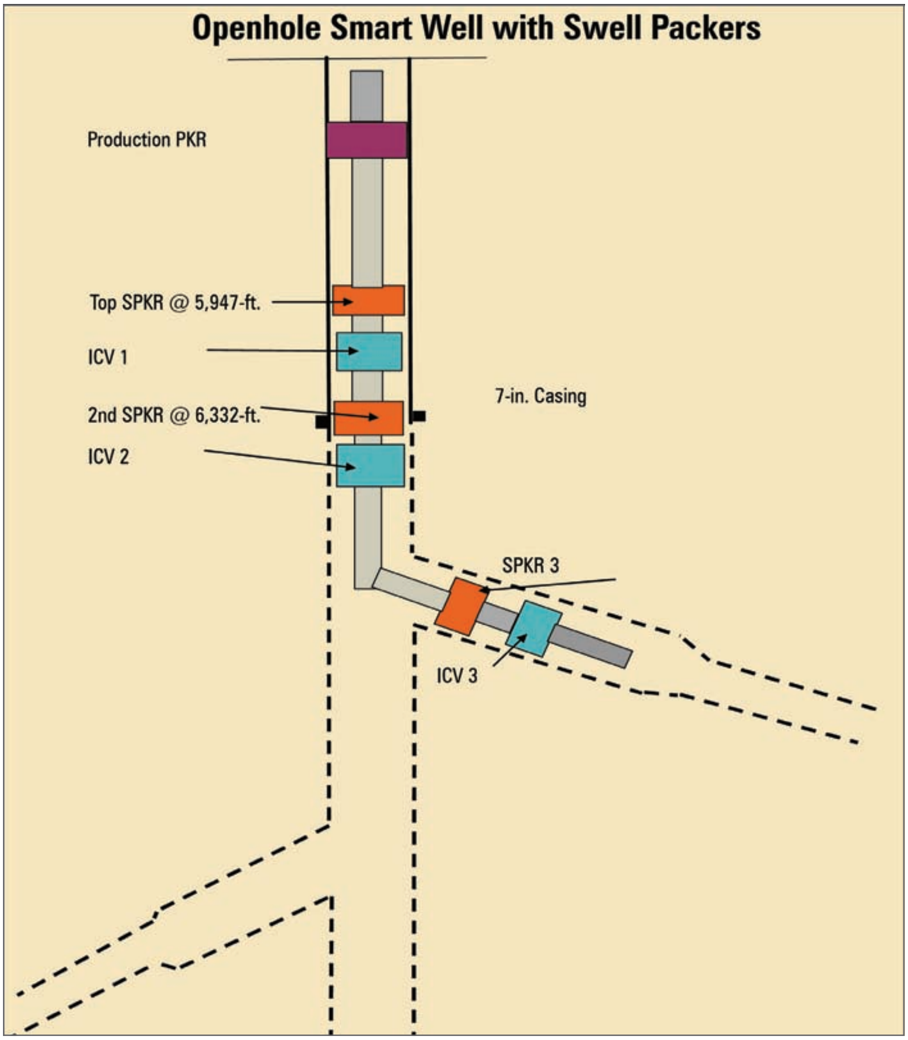


Figure 4: Well cross-section and location of completion equipment.
Figure 5: Schematic of Shayba 368 final installation, with swell packers in place.

carbide choke with a metal-to-metal sealing surface that is rated to 7,500 psi differential in either direction. Each ICV contains a locking mechanism to lock the choke on close position and prevents inadvertent functioning due to downhole conditions. In case of any damage to the hydraulic control lines, the ICVs are "fail as-is."

Each of the three downhole valves has an independent open line and a common close line that is shared by the three valves. Hydraulic pressure applied on either side of a piston at the ICV to move the valve to the "open" or "closed" position.

Two sets of pressure and temperature sensors were installed in the well to measure the downhole pressure and temperature. The sensors are placed at 100 ft TVD apart from each other so that the density of the tubing fluid can be inferred from the pressure gradient between the sensors. The sensors are placed above the upper production packers and measure the properties of the combined flow stream from the motherbore and laterals.

The retrievable production packer was used to anchor the tubing in the 7-in. casing. This is a hydraulically set packer with bypass ports for the hydraulic control lines.

SUMMARY OF PROGRAM

The intelligent well completion operation was conducted as follows:

1. Retrieve existing completion.
2. Extend the 6 1/8-in. open-hole section.
3. Make 6 1/8-in. open-hole windows and drill laterals from motherbore.
4. Run clean-up trips in motherbore.
5. Run completion in single trip. The completion consists of tubing centralizers, inflow control valves, swell packers, tubing, production packers and permanent gauges.
6. Land tubing hanger.
7. Function test interval control valves.
8. Set and test upper production packer.
9. Open SSD above production packer and displace upper annulus to inhibited diesel.
10. Close and test SSD.
11. Install tubing barrier. Nipple down BOP and install tree.
12. Open each downhole valve and clean up each zone sequentially.

PREPARATION, CLEAN UP

Prior to running the completion, a clean-up assembly was run in hole to clean up the motherbore to the lower-most depth of the completion. A second objective of this clean-up trip was to verify if assemblies will remain in the motherbore while going past the two lateral windows. The windows for both the laterals are in the lower section of the hole as the windows were cut without using whipstocks. The clean-up string went past the upper window but held up at the lower window. The string was freed from the window and moved 70 ft with increasing drag before stopping again. There was no confirmation if the clean-up string was in the motherbore or 70 ft in the lower lateral.

ASSEMBLY, INSTALLATION

A decision was made to continue with the completion even though the clean-up assembly was held up 70 ft below the lower window. The installation of the intelligent well completion assembly to the clean-up depth provided Saudi Aramco with a three-zone smart well completion, with each valve controlling inflow from each of the three sections. It did not matter if the lower valve and swell packer went inside the lower lateral.

The completion string consisted of five .800-in. lower tubing centralizer, 3 ½-in. interval control valve for each zone and swell packer to isolate the zones from each other and production tubing to space out the assemblies with respect to the laterals. The upper section of the completion consisted of the 7-in. production packer, sliding side door, dual permanent gauges and tubing to surface.

The completion string was held up at the upper window. The assembly moved after working the string, but the drag increased as it moved for another 60 ft. The risk of buckling the 3 ½-in. EUE tubing prevented the application of more load on the completion string, and a decision was taken to set the completion at this depth. See Figure 5 for final completion drawing.

Step #	V1	V2	Rate MBOD	Remarks	
1	○	○	7.6	L1 + MB + L2 =7,600	
2	●	○	7.4	0 + MB + L2 = 7400	MB + L2 = MB + L2 + L1
3	●	●	0	0 = 0	
4	●	○	7.4	Step 4 = Step 2	
5	○	○	7.4	Step 5 = Step 1	
6	○	●	5.0	L1 + 0 + 0 = 5000	L1 < MB + L2

Table 3: Summary of test results from all three laterals. Valve 1 (V1) controls the upper-most lateral (L-1), while Valve 2 (V2) controls the motherbore and the lower lateral.

ANALYSIS AND TESTS

The first field installation was performed in an existing open-hole tri-lateral well and was performed to provide inflow control in the laterals. The well was part of a workover program to convert the existing 1-km wells to tri-lateral wells to improve their performance by increasing the reservoir contact and improving the well productivity. This reservoir contact for this well was increased from 1-km single lateral to 6-km trilateral well with an average lateral length of 2 km.

The original well was drilled conventionally by drilling laterals bottom up and kicking off on the low side. This drilling convention resulted in placing the completion off-bottom. It is believed that the completion fell into the first low-side lateral, resulting in setting the upper-most swell packers up in the 7-in. liner. As a result, the upper-most ICV is not being used. The second ICV is controlling the upper lateral while the lower-most ICV is controlling the two bottom laterals in commingled flow.

Table 3 summarizes the test results from all three laterals. As indicated, Valve 1 (V1) controls Lateral-1, which is the upper-most lateral whereas Valve 2 (V2) controls both the motherbore and the lower lateral.

A review of the production and pressure data from this well indicates the swelling packers to be holding thus, providing lateral isolation. Furthermore, test results indicated that when all the laterals are opened to production, the total flow rate is 7.6 MBOD (step 1 and step 5) where as when only V2 is opened, the motherbore and Lateral-2 contribute to a total rate of 7.4 MBOD. The contribution of the two laterals is almost equal to that of the three laterals combined when opened. This is mainly due to the fact that the motherbore and Lateral-2 are in a better permeability compared with Lateral-1 and therefore the motherbore and Lateral-2 will dominate the flow when all the three laterals are opened to production.

In addition, test data indicated that when the upper-most lateral (L-1) is opened to flow with V2 being closed (step 6), the production from Lateral-1 is 5 MBOD, suggesting that this lateral has the potential to produce when the other two laterals are closed.

The above test was conducted when all the downhole chokes were fully opened and the surface choke was set at 25% opening. Currently, the well is producing at a rate of 6 MBOD with 1% water cut at an average pressure draw-down of 60 psi, compared with a pre-workover rate of 1 MBOD and water cut of 15%.

CONCLUSIONS

A second well was drilled and completed utilizing the same swelling packers and open-hole ICV concept. In the second well, the completion was run in a dual later to avoid the problem of running the liner into the lower lateral drilled on the low side. This completion ran as planned and is being evaluated. Future wells are being planned for tri-lateral wells. In these new wells, the laterals will be drilled top-down utilizing high side kick-offs to avoid problems deploying the completion to TD. The success of this new-generation open-hole intelligent well will provide Saudi Aramco with new opportunities to optimize well cost without sacrificing required inflow control.

Based on the success of these first two completions, Aramco has since utilized the swelling packers to provide open-hole annular isolation in its passive ICV completions for long horizontal completions. By utilizing swelling packers, it is possible to place more annual barriers (one every 100 ft of horizontal section) to provide better compartmentalization and hence, better inflow conformance resulting in increased well recoveries and prolonged water breakthrough.

Saudi Aramco is also planning to utilize fiber optic permanent monitoring devices to reduce or replace the need for wireline deployed production logging tools in these compartmentalized smart well completions. These monitoring systems will allow Saudi Aramco to manage the production from these smart wells more efficiently while reducing the number of well interventions.

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