TRACER EVALUATION OF THE FIRST OPENHOLE GRAVEL PACK WITH AICD IN ULTRA DEEP WATER

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RESUMEN

La ejecución del Empaque de Grava en Pozo Horizontal Abierto (Hz-OHGP) en aguas ultra profundas (superiores a 1500 m) exige el uso de las mejores tecnologías disponibles. Para el Proyecto Atlanta, en documentos anteriores (OTC-25813, SPE-174893 y SPE-174896) se proporciona una descripción detallada de los primeros dos pozos completados con éxito con Hz-OHGP. Luego de la completación y el conocimiento del flujo de los dos primeros pozos, se determinó que el tercer pozo se beneficiaría del uso de AICD (dispositivo autónomo de control de flujo de entrada) en las pantallas, que traería nuevos desafíos además de las consideraciones del diseño habitual de pozo Hz-OHGP de aguas profundas

Para evaluar la contribución del flujo de petróleo a lo largo del pozo, el ingreso de agua y la efectividad del AICD, se instalaron trazadores químicos de polímeros sólidos para petróleo y agua en 6 posiciones a lo largo del pozo.

Este documento detallará el diseño de completación y los resultados proporcionados por los trazadores de petróleo y agua que muestran el flujo de petróleo cuantitativo de cada zona del pozo durante un período de tiempo prolongado y los resultados de la respuesta del AICD debido al aumento del corte de agua a lo largo del tiempo desde la zona de producción.

INTRODUCTION

Atlanta field is a post salt oil field in Santos basin, located in a pre-salt exclusion zone, about 185 km southeast of Rio de Janeiro, in ultra-deep waters of 1,550 m (5,000 ft). It was discovered in 2001, and Enauta has been operator since 2012. Estimated reserves, considering 8 producer wells, is 103 MM bbl with 1.29 billion bbl in situ oil volume. The field's Eocene reservoir has 82-94% net-to-gross, very high permeability (up to 5D), 36% porosity, and produces 14° API oil, with a high viscosity of 230 cP, low sulfur content and high TAN (9,8 mg KOH/g). Long horizontal sections in the reservoir, large diameter production strings, robust sand control (Hz-

OHGP) and high-powered deep-set electric submersible pumps (ESP) are required to assure commercial production. Using a pioneering flow assurance concept, an artificial lift skid (ALS) located at the mudline is planned for in-well ESP backup (See Figure 1).

The first reservoir appraisal well, drilled by previous operator, had a vertical cased hole gravel pack completion with 91 m of perforations. The well had poor productivity and high skin, suggesting that a HZ-OHGP would be required for field development. The sandstone is characterized as poorly sorted with non-uniform grain size, and a low burial depth (800 m) with a low frac gradient (0.5 psi/ft). These two issues challenged HZ-OHGP completions.

During the appraisal phase, the first attempt to complete a well for testing the horizontal concept for production, with a HZ-OHGP, was not successful. The well was completed with 10 ¾-in. casing, 9 ½-in. open hole, and 5 ½-in. screens containing 4 ½-in. wash pipe. Returns were taken via the choke and surface return line, causing significant back pressure to the formation, impacting overall gravel pack placement. Also, during the drilling phase, an LCM pill was left in the open hole for running the screens. During gravel pack (GP) pumping, this pill plugged the sacrificial screen, terminating the operation. The well was left as a stand-alone-screen (SAS) completion. A well test revealed poor productivity and sand production clogged and burned the ESP.

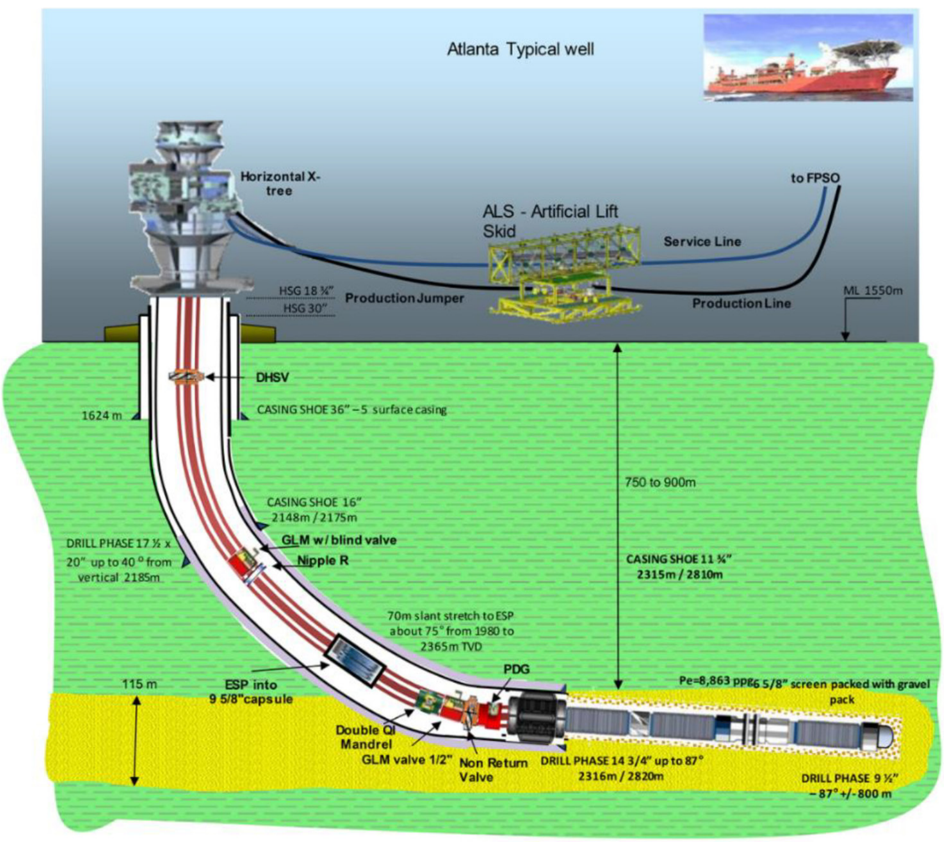

Figure 1. Atlanta typical well.

As described by Marsili, 2015, the development of the Atlanta Field is composed of two phases: The Early Production System (EPS) and the Definitive Production System (DPS). At the beginning of EPS, two long (about 800 m) horizontal wells were successfully completed with HZ-OHGP under new operatorship in 2012. Another eight wells were planned for the full development (DPS). These wells had larger 6 $^{5}/_{8}$-in. screens to minimize the open hole annulus and accommodate larger 5-in. wash pipe to increase flow area and reduce friction in the return flow path up the wash pipe. Risk of gravel pack failure was further minimized by using light weight gravel, reducing carrier brine weight, and adding friction reducer in the carrier fluid to reduce bottom hole pressure and enable packing below fracture pressure. This reduced the risk of fracturing induced leak off and premature bridging. A retractable casing shoe eliminated a large diameter rathole which can cause premature bridging in this section at the start of the alpha wave. Gravel pack placement was planned using multiple alpha waves and reducing gravel concentrations from the first HZ-OHGP attempt.

AICD COMPLETION

The Atlanta´s Eocene reservoir has a large active aquifer below the oil rim, as shown in Figure 2, depicted in Figure 3. Despite this extensive aquifer, reservoir simulations based upon geological available inputs indicated that low water production would be observed during the EPS phase. The FPSO (Floating, Production Storage and Offloading) refurbished for the EPS was designed to treat only low volumes of produced water.

Following risk prevention philosophy used to guide the Atlanta project at the beginning of the planning phase, it was determined that use of a flow / flux equalizing technology in the horizontal section would be beneficial to reduce water coning, therefore, delaying water breakthrough. This technology was avoided for the first two development wells over concerns about gravel packing in a narrow pore-fracture pressure gradient window.

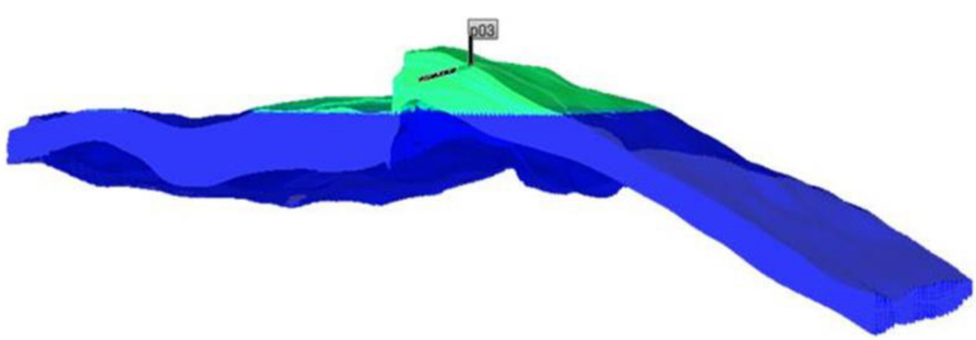

Figure 2. Oil/Water Contact and a typical Atlanta well.

Better understanding of the minimum horizontal stress (from a microfrac/extended leak off test) and improved modeling of HZ-OHGP in low pressure environments using data from the first two wells provided an opportunity to apply AICD technology for the third well. At a minimum, by using the available gravel packing strategy, the screens were expected to be covered by the alpha wave, providing reasonable protection to the screens during the production phase.

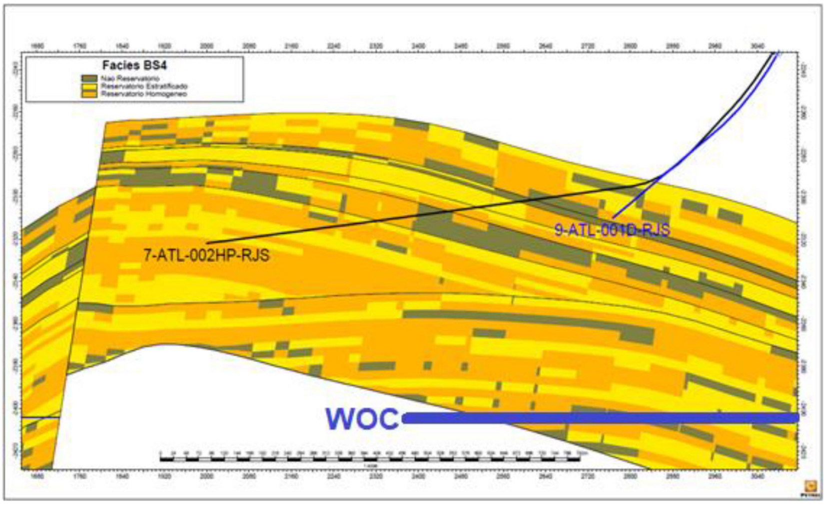

Figure 3. Detail of Atlanta reservoir and WOC.

In addition, the “self-healing” nature of the chosen AICD, would effectively become plugged by the gravel pack proppant in the case of screen failure. This helped to facilitate the decision to implement and realize the benefits of AICD technology in this already challenging environment.

After carefully analyzing the options available, it was decided on the use of a fluidic diode type AICD (Fripp, 2013).

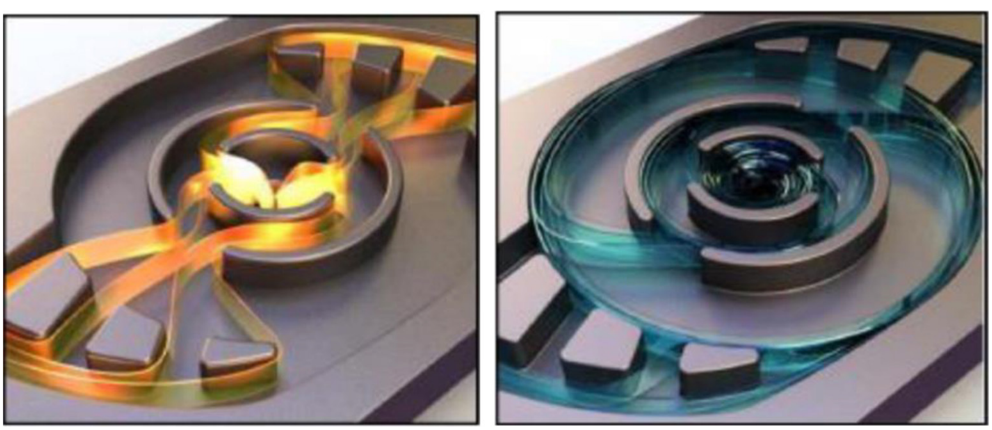

Figure 4. Fluidic Diode AICD schematics.

The real size of each AICD insert can be visualized in Figure 5. This figure also shows the position of the inserts in the screen joint and how the inserts are connected with the filter media.

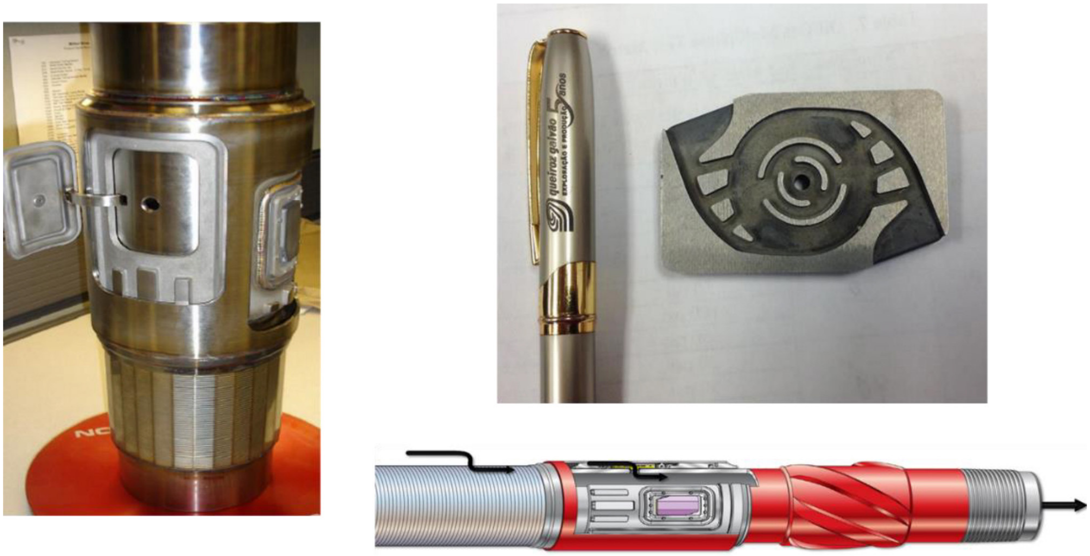

Figure 5. AICD real size and connection with the filter media

OIL AND WATER TRACER POSITIONING

A very important phase of Atlanta´s well construction and reservoir evaluation, was the use of oil and water chemical solid polymer tracers integrated with the sand control screens.

Although Atlanta´s reservoir is a unique hydraulically connected body, geologically it comprises 6 layers, with 6 different facies, showed in Figure 6.

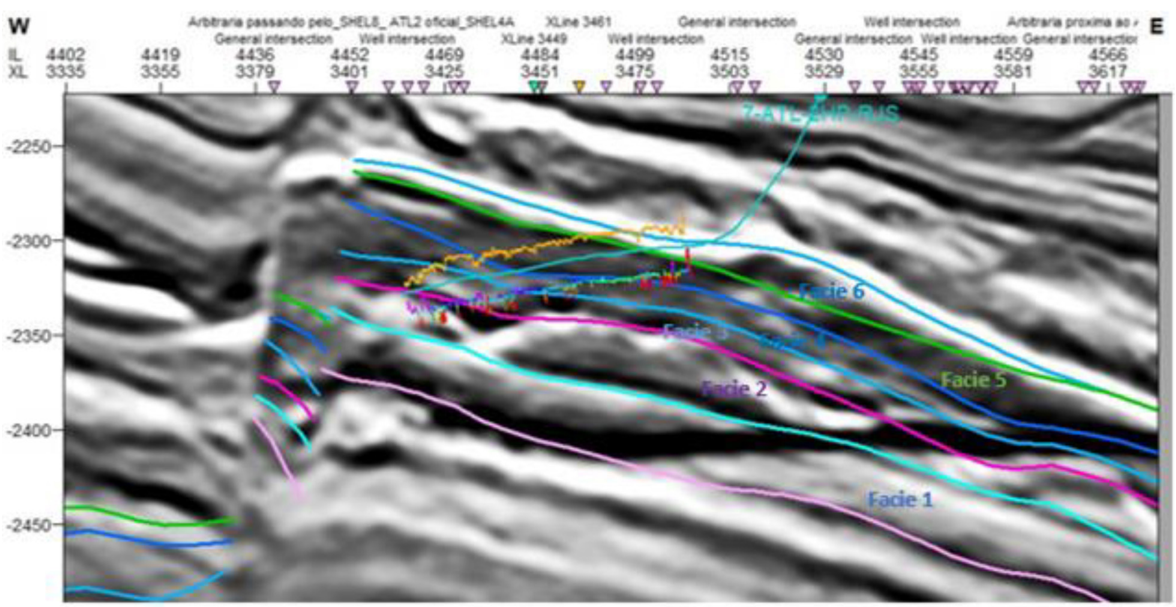

Figure 6. Seismic showing Atlanta´s reservoir facies.

These six facies are highlighted in Figure 7:

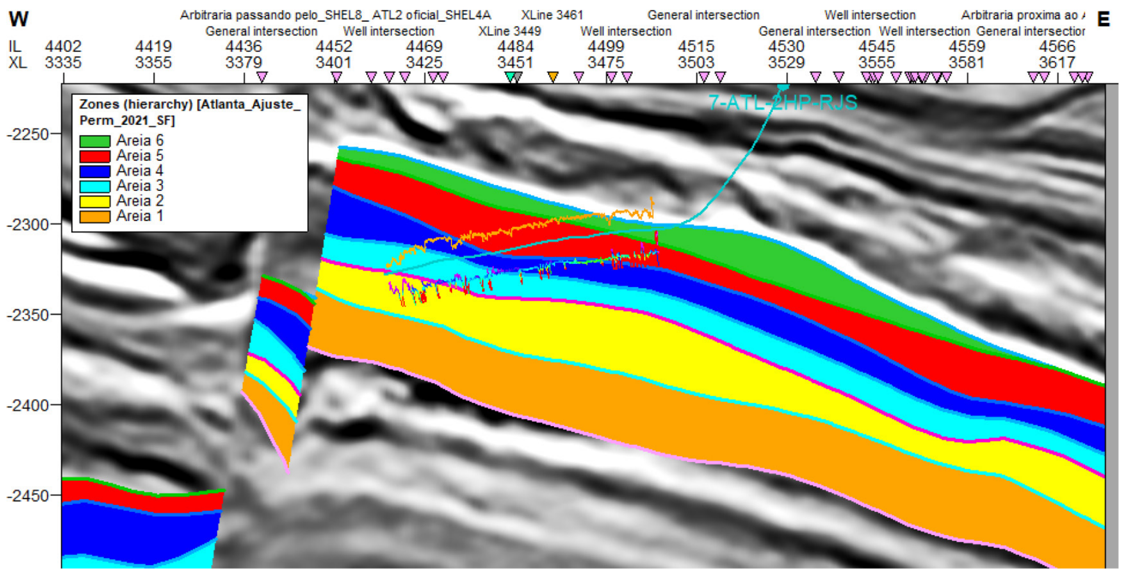

Figure 7. Atlanta´s reservoir facies.

These different facies have permeability and porosity heterogeneities, as shown in Figure 8 and Figure 9.

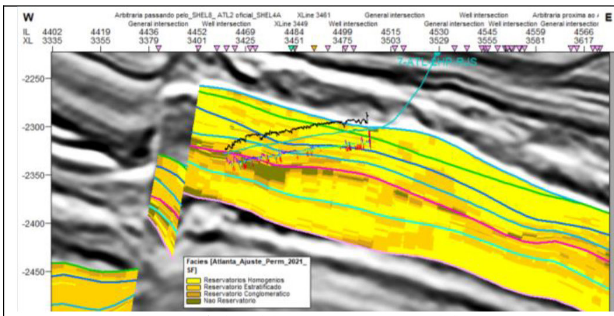

Figure 8. Permeability heterogeneities in Atlanta's reservoir facies.

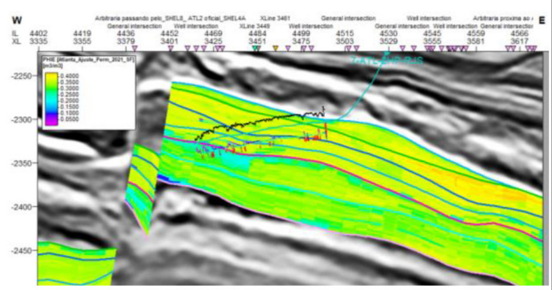

Figure 9. Porosity heterogeneities in Atlanta's reservoir facies.

Because of these heterogeneities, an uneven production of each layer was expected, that would affect the waterfront arrival to the well, as depicted in Figure 10 showing the expected water saturation after 2 years of production.

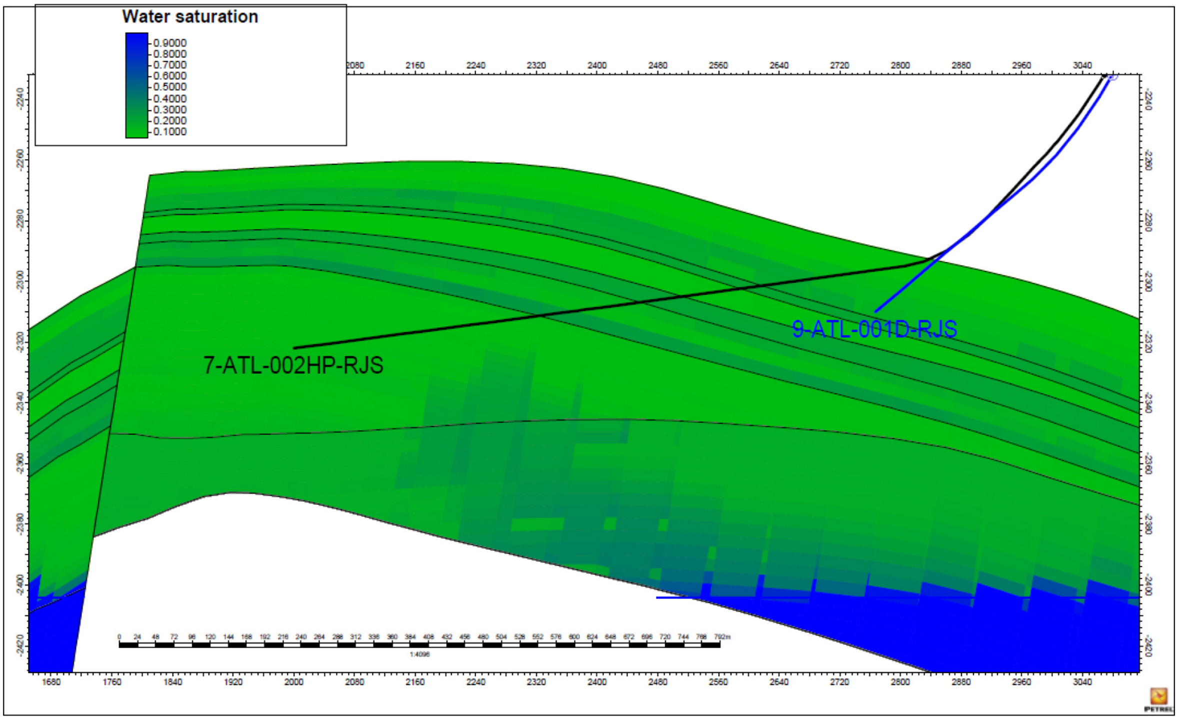

Figure 10. Expected water saturation after 2 years of production.

Considering the expected water arrival and geological heterogeneities the oil and water tracers were distributed along the well as detailed in Figure 11 and Figure 12.

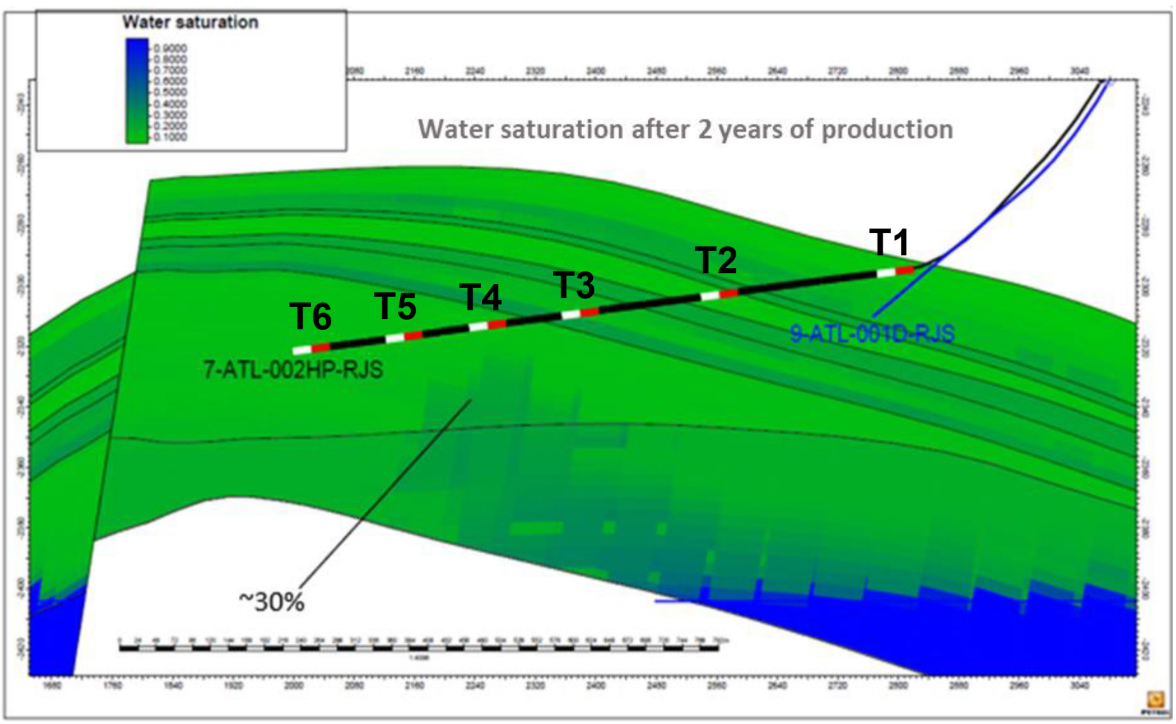

Figure 11. Tracer (Oil & Water) distribution and expected water saturation.

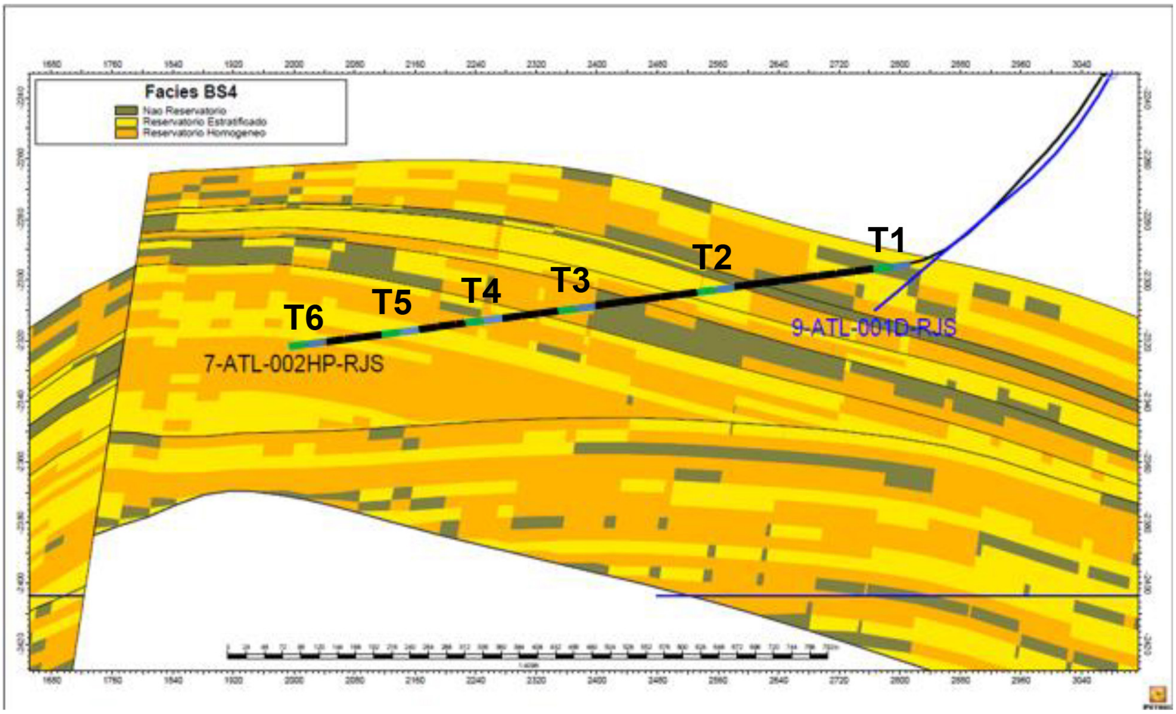

Figure 12. Tracer (Oil & Water) distribution and rock reservoir heterogeneities.

Flow Simulations

The very first step for using inflow control devices (ICD) is to correctly simulate the flow with and without equalization. To simulate the flow at the reservoir, an 800 m horizontal (88 degrees) well was inserted into the geological model, with the 6 facies described above containing the permo-porosity heterogeneities of the reservoir, as shown in Figure 13 (Apud Pedroso, 2020 - SPE199325).

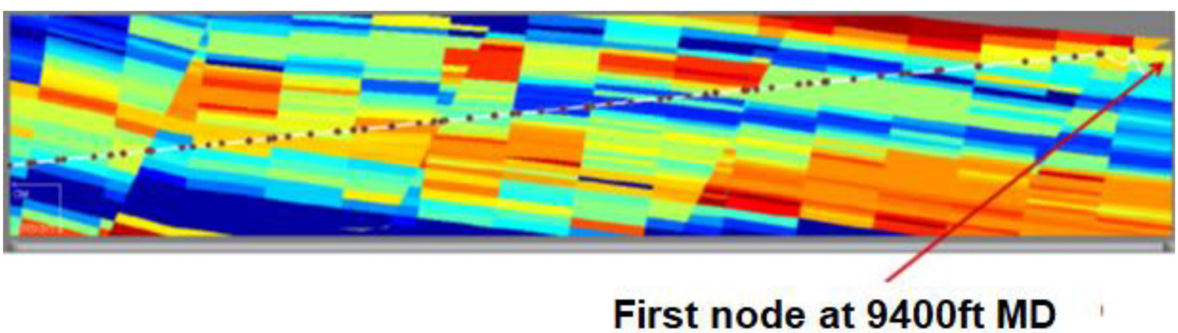

Figure 13. Horizontal well trajectory in Atlanta reservoir for reservoir simulation.

After considering the needs to equalize the flux, reduce produced water and maximize oil production, 4 ICD screen distribution scenarios were deeply analyzed. The best results are shown in Figure 14.

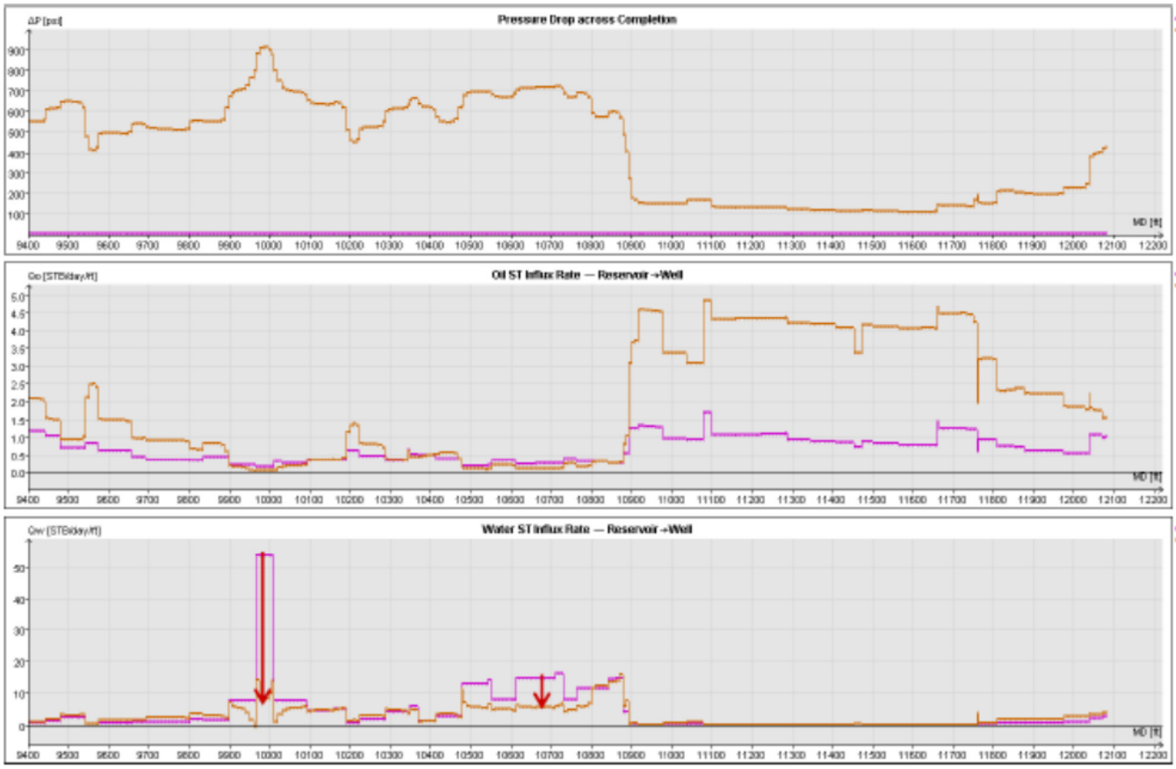

Figure 14. Simulated oil & water production for the chosen ICD screen distribution.

Based on extensive reservoir simulations, to equalize the flux and maximize the production, a set of screens with 3, 6 and 8 inserts were distributed through the horizontal section, as shown in Figure 15. The best simulated configuration, which was implemented in the third well, ATL-4 consists of 6 screens with 8 inserts, 31 screens with 3 inserts, 31 screens with 8 inserts and 1 screen with 6 inserts.

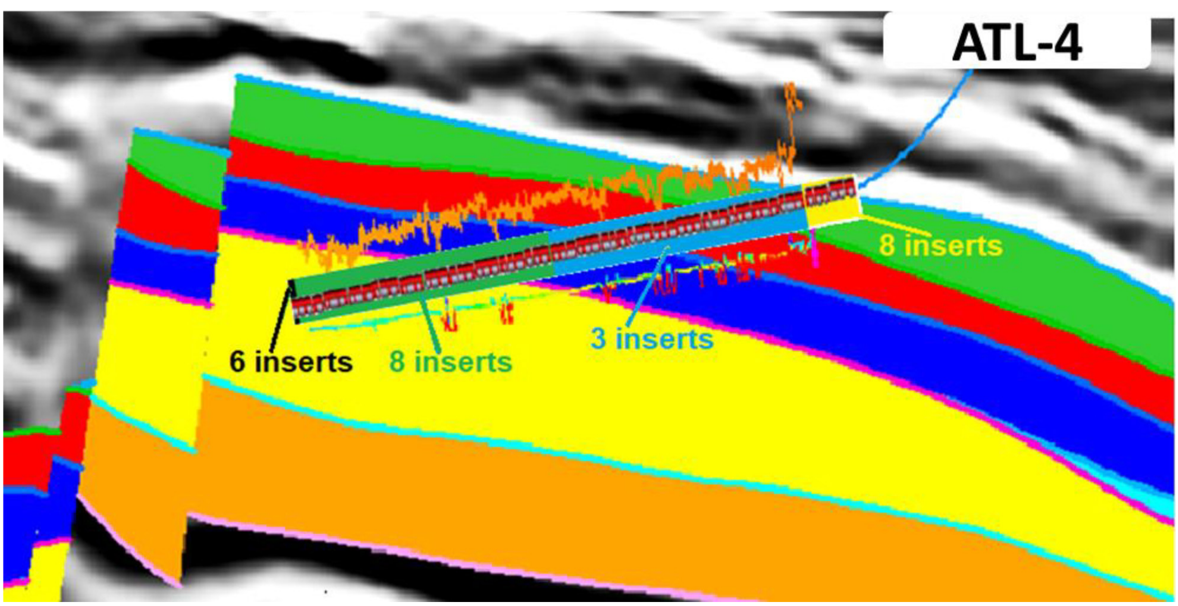

Figure 15. AICD Screens distribution and Atlanta reservoir facies.

AICD TESTS

The selected AICD was tested in a third-party laboratory (SWRI - Southwest Research Institute) to confirm efficiency and pressure drop added during the gravel pack pumping. Biphasic (Figure 16) and triphasic loops (Figure 17) were used to simulate the flow of water, oil, and gas in different proportions.

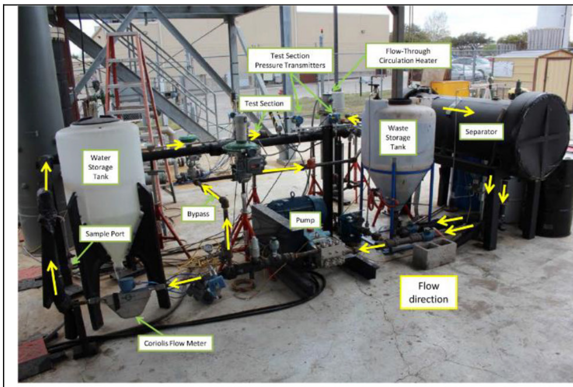

Figure 16. Biphasic loop (source: SwRI)

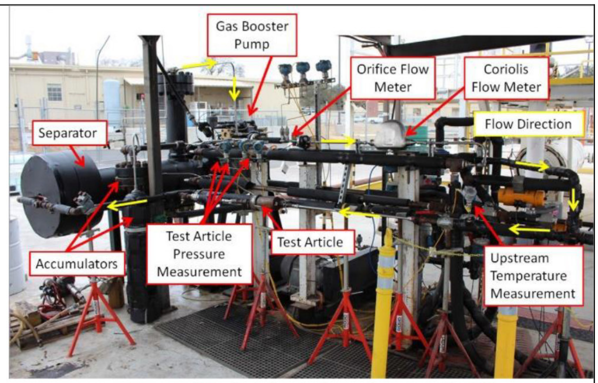

Figure 17. Triphasic loop (source: SwRI)

The results are summarized in Figure 18, Figure 19 and Figure 20.

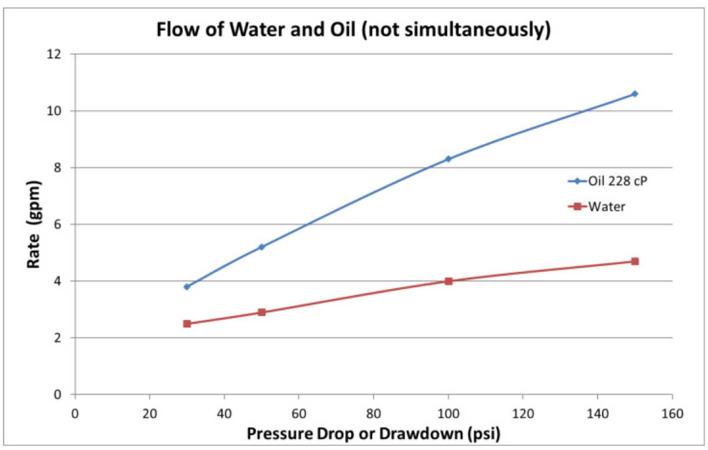

Figure 18. Pressure drops (necessary drawdown) across one AICD insert.

From Figure 18, it was possible to conclude that a big pressure drop would be expected during HZ-OHGP when pumping aqueous non-viscous brine, especially at the end of the beta-wave.

The second point found was that the AICD insert is very efficient to selectively produce more viscous fluid (or heavy oil) instead of water.

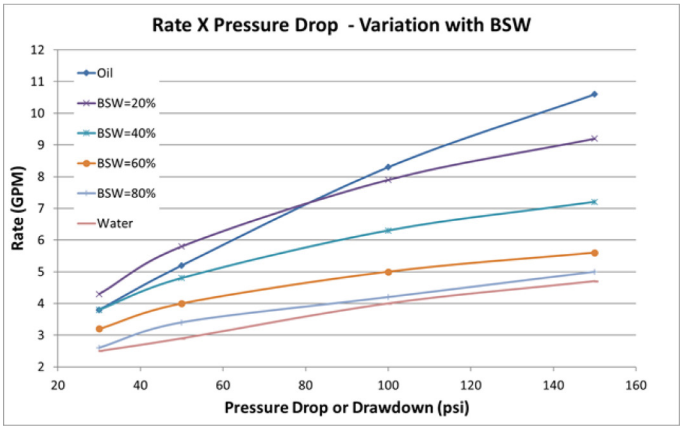

Figure 19. Variation of pressure drop with BSW

This tendency to produce more viscous fluid could also be verified in Figure 199, where the results revealed that the higher the BSW (%), the higher the necessary drawdown to flow.

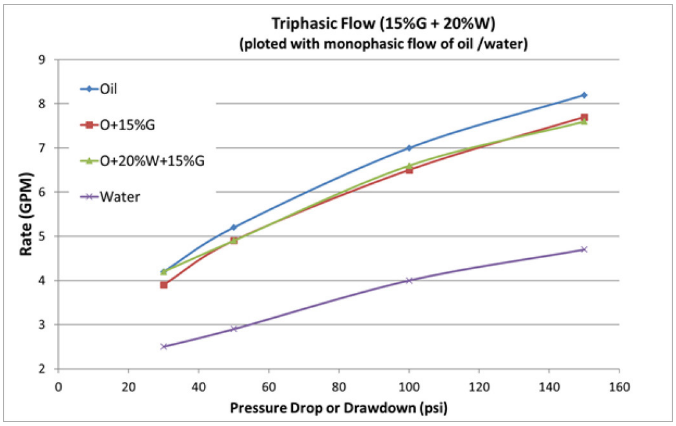

Figure 20. Triphasic Flow.

In Figure 20, the efficiency of the AICD was verified with the expected production of 15% gas (GVF) across the screens.

PUMPING STRATEGIES

Atlanta´s gravel pack pumping was a challenge in itself since this was the first well completed worldwide using AICD's in ultra-deep waters and the Atlanta formation low fracture gradient (0,508 psi/ft) added complexity to the job due to the restrictive features of the AICD, especially with the low-viscosity (brine) restriction imposed by the AICD, as previously stated. Also, it was the first well worldwide to be completed with AICD and 6 5/8" premium screens.

The high pressure drop imposed by the AICD posed a challenge to the traditional alpha-beta packing technique of a standard Hz-OHGP. To execute a complete pack, the pumping strategy had to be completely reevaluated, taking into consideration all key variables and possible solutions.

Initial Simulations

The initial simulations considered previously used solutions to extend the operational window, including:

- Rathole Zero technology, by using a retractable shoe in the production casing
- Back pressure minimization with the use of flowline flowmeter and five inches wash pipes.
- Low density proppant in both, alpha and beta waves.
- Reduced carrier fluid density.
- Progressive pump reduction (multiple beta wave).
- Use of friction reducer.

Nevertheless, even with all these features, simulations indicated that 94% of the open hole would be covered. In normal conditions, it would be completely acceptable for a gravel pack design, but the use of a high power electrical submersible pump (ESP) demanded the most robust sand control possible.

To increase the screen coverage, the follow strategy was simulated and adopted:

- The use of a conventional sacrificial screen, to allow the alpha wave to be pumped with conventional pumping rates (6 – 8 BPM) and using conventional density proppants (2,7 g/cm^3).
- Low density proppant (1,34 g/cm3) in beta wave
- Sonic log pos-processing for better caliper evaluation
- Low proppant concentration (0,25 lb/gal) at the beginning of the job
- Decreasing pumping rate to the minimum limit
- Pioneer use of 4” wash pipe inside the 6 5/8” screens
- The use AICD screens into the casing, instead of blank pipes, as showed in Figure 21.

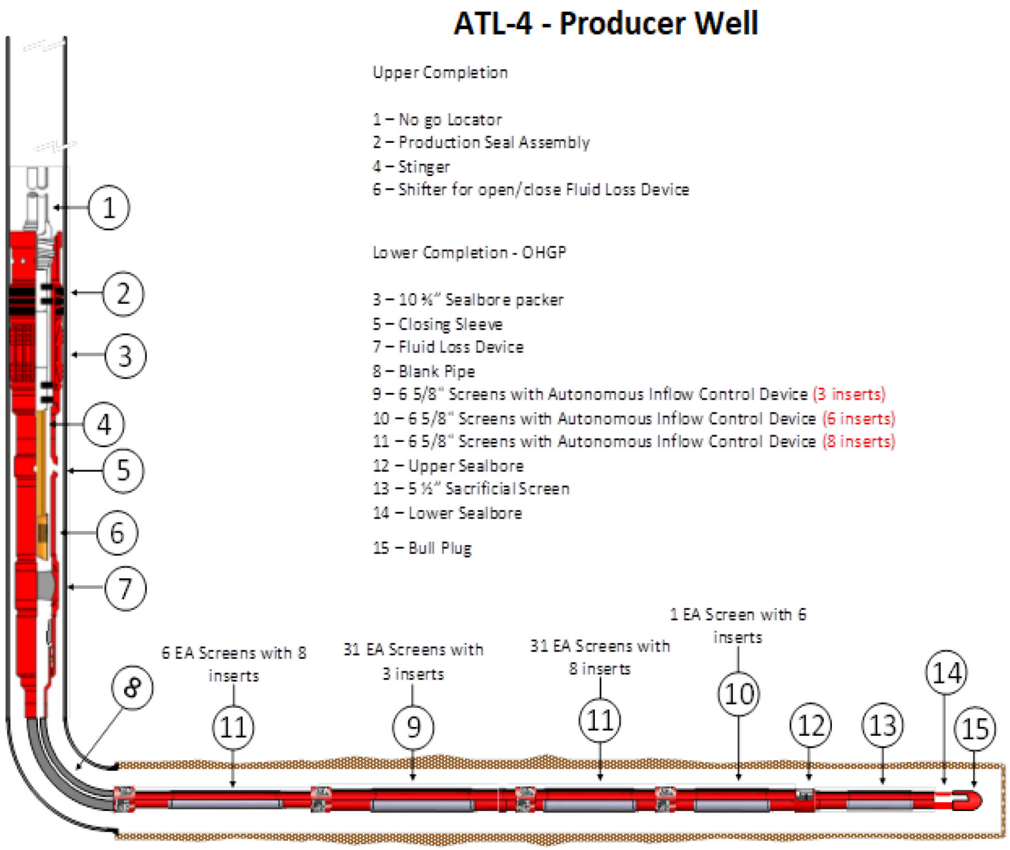

Figure 21. Gravel pack assembly and AICD screens distribution.

Final Simulation

With all these considerations, the final simulation indicated that the hole could be packed with 100%, finishing the job with an extremely low pumping rate of 1.5 bpm, as shown in Figure 22:

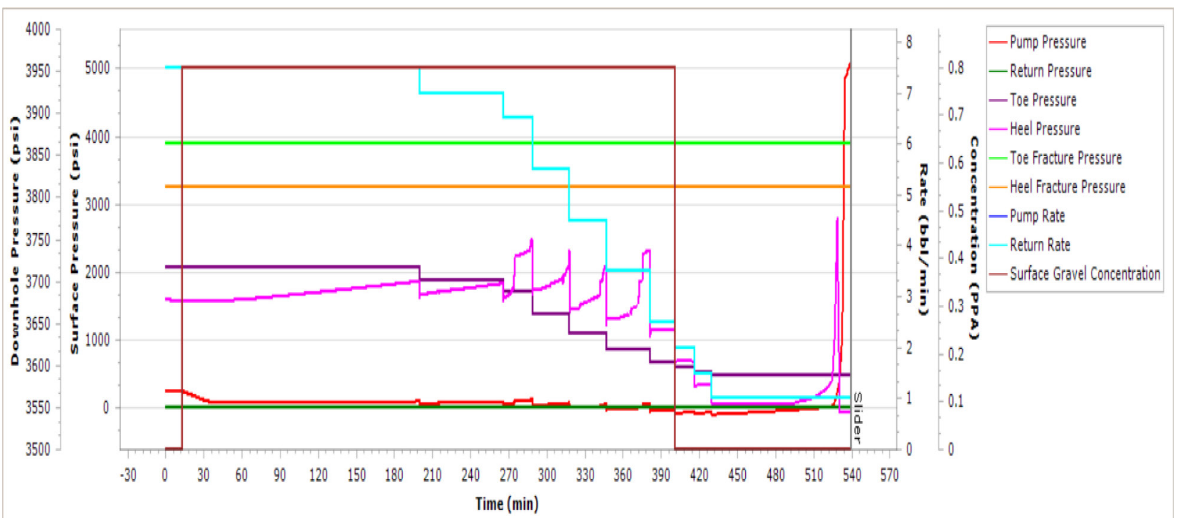

Figure 22. Gravel pack pumping final simulation

Gravel Pack Pumping

In April 2019, with pumping strategy in place, the AICD screens were installed, and the gravel pack job was then pumped starting at 6.5 bpm and 0.5 ppg. The rate was reduced in steps during the job, achieving 1.0 bpm at the end, while the average proppant concentration remained the same until swapping to the light- weight proppant, where it was pumped at 0.25 ppg. As expected, the well was completed with a 100-percent-complete pack around the screens along 805 m of open hole section. 41,500 lb of LWP (Light weight proppant) 16-20# and 17,900 lb of ULWP (Ultra-LWP) 16-20# were pumped, placing 755 ft³ of proppant in the open hole section. The chart of this unique operation is shown in Figure 23.

It is very interesting to observe the rapid increase in pumping pressure at the final part of GP pumping, despite the aggressive reduction of pumping rate and the reduction of bottom hole pressure. This indicates the high pressure drop across the AICD due to the low number of inserts of the AICD screens.

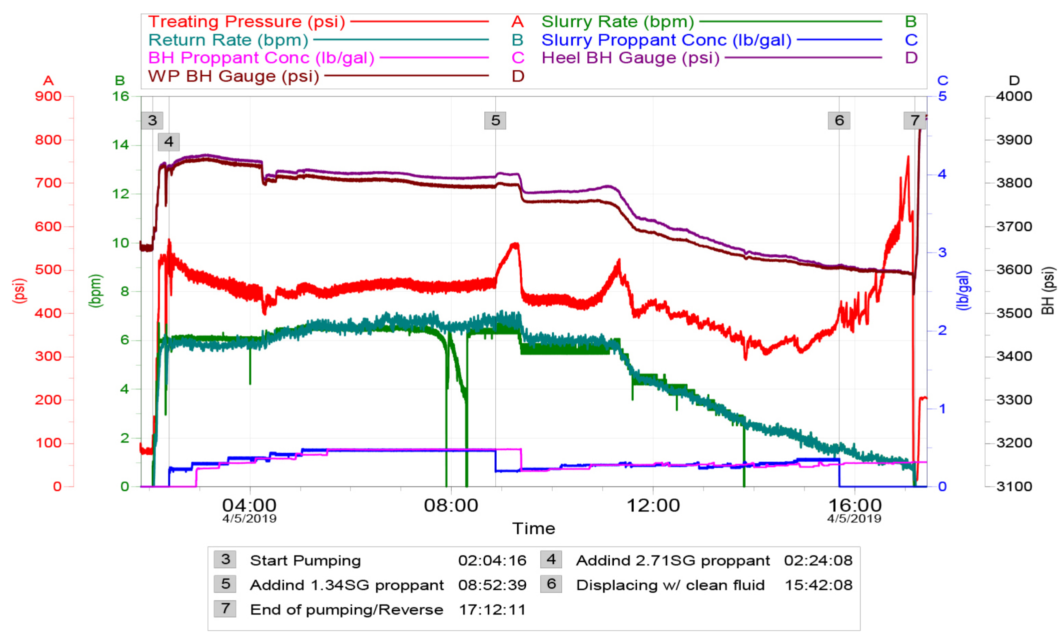

Figure 23. Gravel pack pumping chart

Packing Test

After the screen out and reversing the proppant excess, the gravel packing pack was tested. High pumping pressure was observed, at low pumping rates, without changing the bottom hole pressure (Figure 24), indicated that the annular was packed inside the casing, assuring that the AICD positioned inside the casing would not jeopardize the horizontal uniformity as planned.

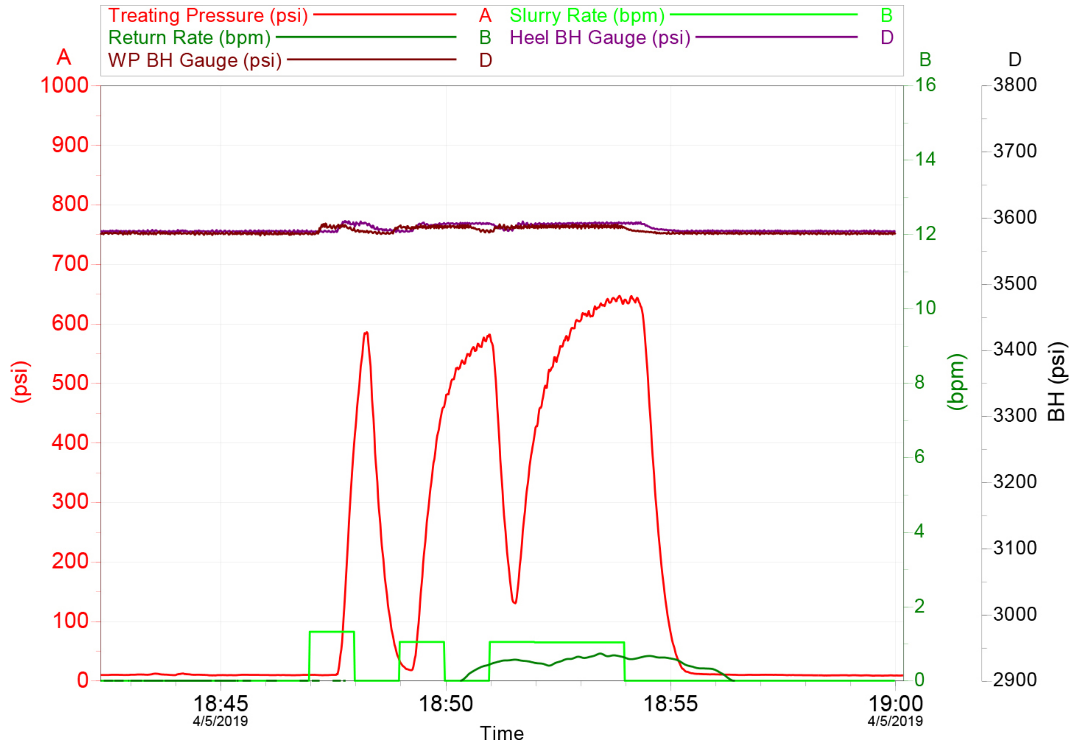

Figure 24. Gravel packing test.

TRACER ANALYSIS

Into each drainage area of the screens, solid chemical polymer tracer strips were loaded (Figure 25), each screen contained a max of 384 strips, applied with sixteen (16) strips end-to-end and/or side-by-side into twenty-three (23) of the drainage layers and two (2) strips into the remaining eight (8) drainage layers to minimize flow restriction through the screen.

Figure 25. Tracers' strips into screen drainage layer.

The position (m) along the well of oil and water tracers, can be seen as shown in Figure 26.

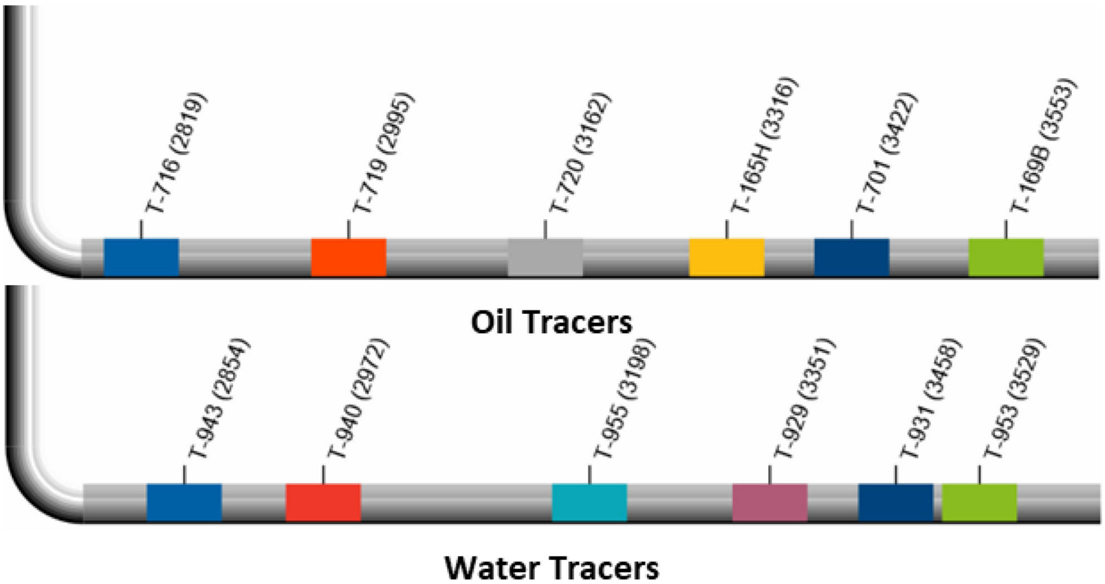

Figure 26. Position (m) of the oil and water tracer along the well ATL-4.

Methodology of Analysis

As can be seen in Figure 27, after startup of the well, during the clean-out, the arrival peaks of the 1st and 3rd tracers were almost at the same time, followed by the peak of the 2nd tracer and after a further 55 minutes the peaks of the 4th, 5th, and 6th tracers.

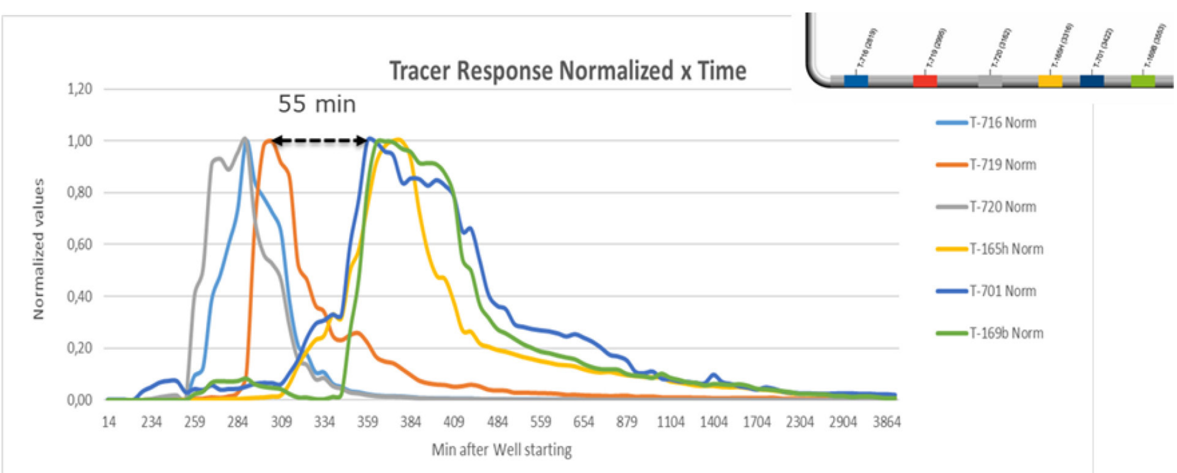

Figure 27. Normalized curves of tracer x Time (min) of sampling after clean-out.

This type of result, where the tracers do not arrive in the order in which they were placed in the well, is not uncommon to observe in analyzes of samples taken during the clean-out of ICD systems, because there is a buildup of tracer “clouds” over time when the well is closed outside of the main production tubing. When the well is flowed the tracer clouds flow into the production tubing at different rates depending upon reservoir properties. Due to the impossibility of performing analysis for contribution of the different zones by using a time transient method that requires sequential production at surface based upon position in the well, the analysis was based on a technique termed tracer decay curve analysis, where the rate at which each tracer curve decays is proportional to relative inflow at that position. The results of the clean out, are presented in Figure 28:

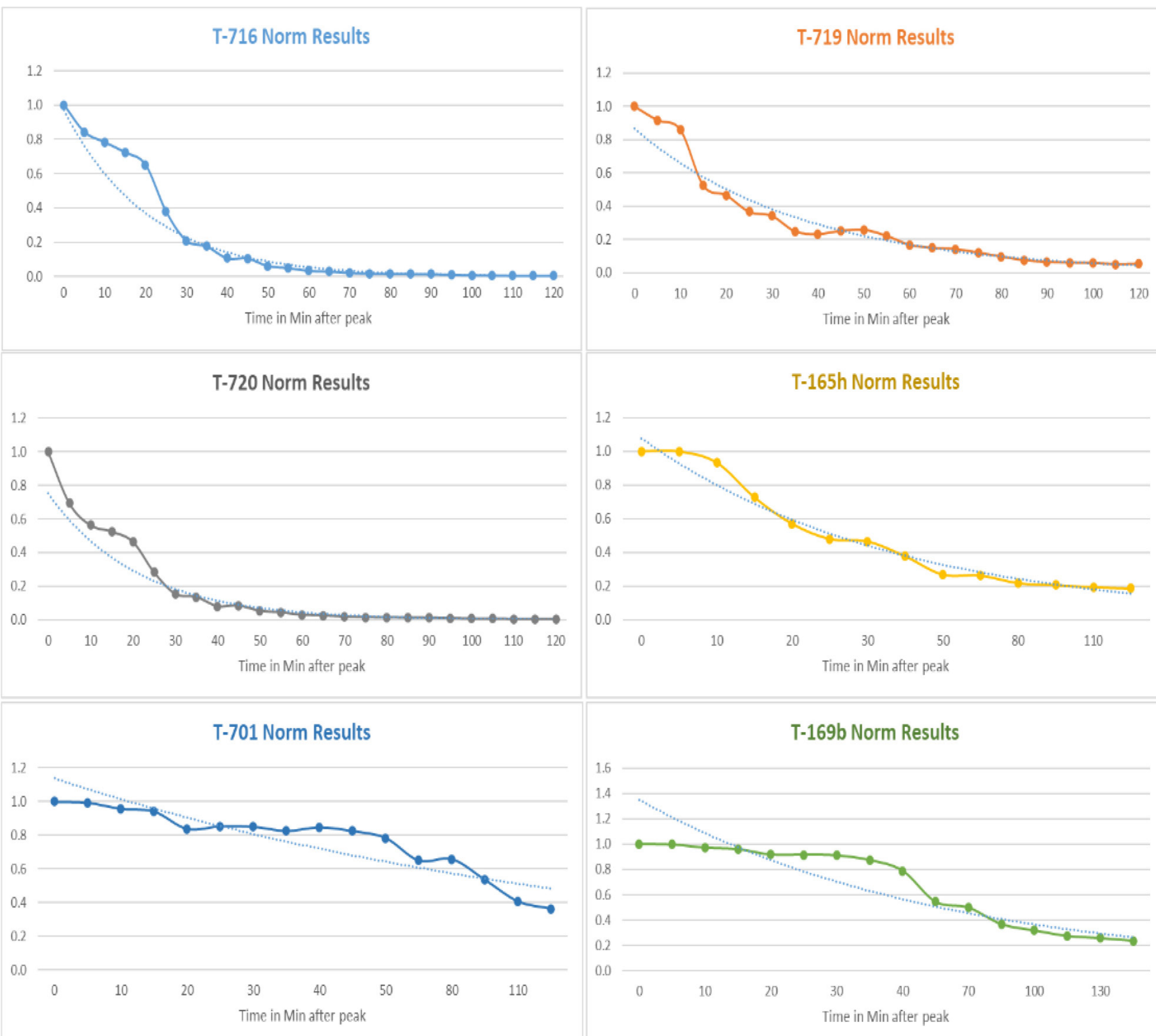

Figure 28. Decay tracer concentration after peak arrival (sampling of clean out flow).

Results of Oil Samples Analysis

As can be seen in the graphs of Figure 29, while in the Clean Out flow, 3rd and 5th Flow, the cloud peaks were well defined, in the 1st and 4th Flow there were plateau formations in the curve of some tracers.

During the 1st Flow, production homogenization is observed along the well; from Clean Out to the 3rd Flow, an increase in the contribution of the Mid-Toe region is observed (34.1% >> 46.6% >> 54.6%), Fig. 30, however in the 4th and 5th Flow, there is a decrease in production in this same area (50.2% >> 17.6%). In the 4th and 5th Flow, the 5th tracer was not detected (T-701, 3422 m).

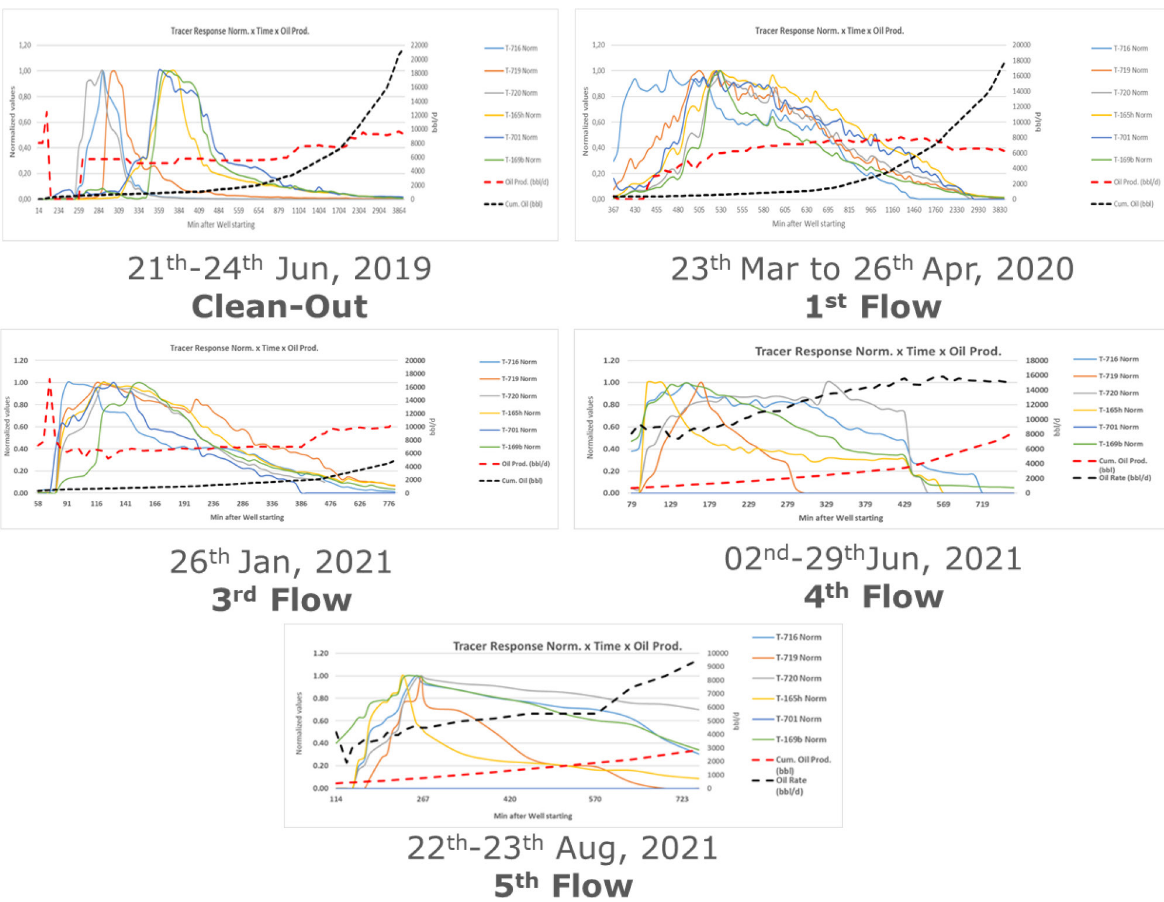

Figure 29. Clean Out, 1st, 3rd, 4th, and 5th Flow (Oil Tracers curves x cumulative oil production x oil rate).

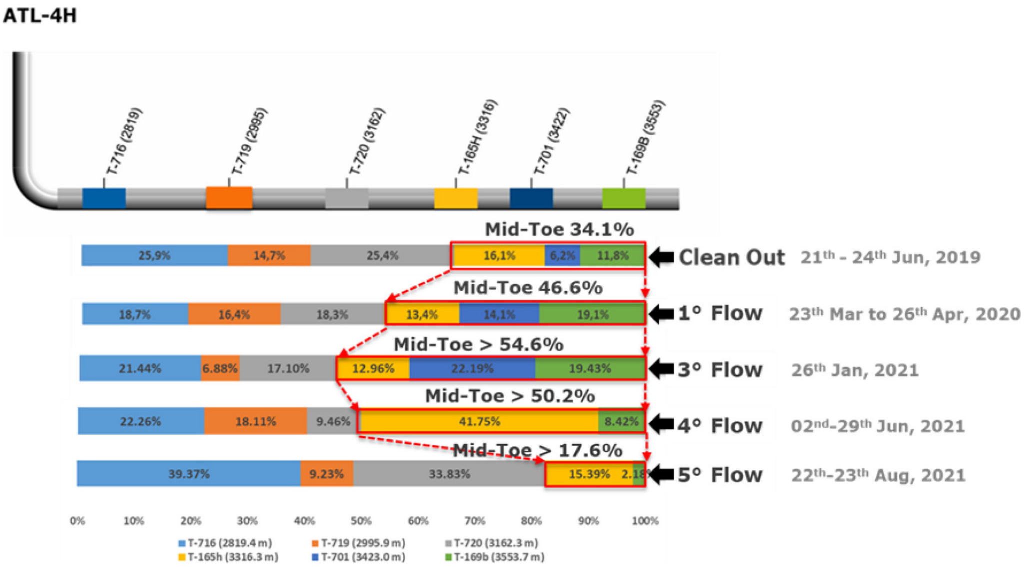

Figure 30. Relative percentage contribution by oil tracer for each flow studied.

Results of Water Samples Analysis

From the oil samples it was possible to extract enough water for water tracer analysis from a limited number of samples.

The association of the release rate of the water tracer and its production concentration in each sample allows the comparative percentage water cut to be established from each zone marked with tracer.

The results are shown below providing relative water cut along the wellbore (Figure 31).

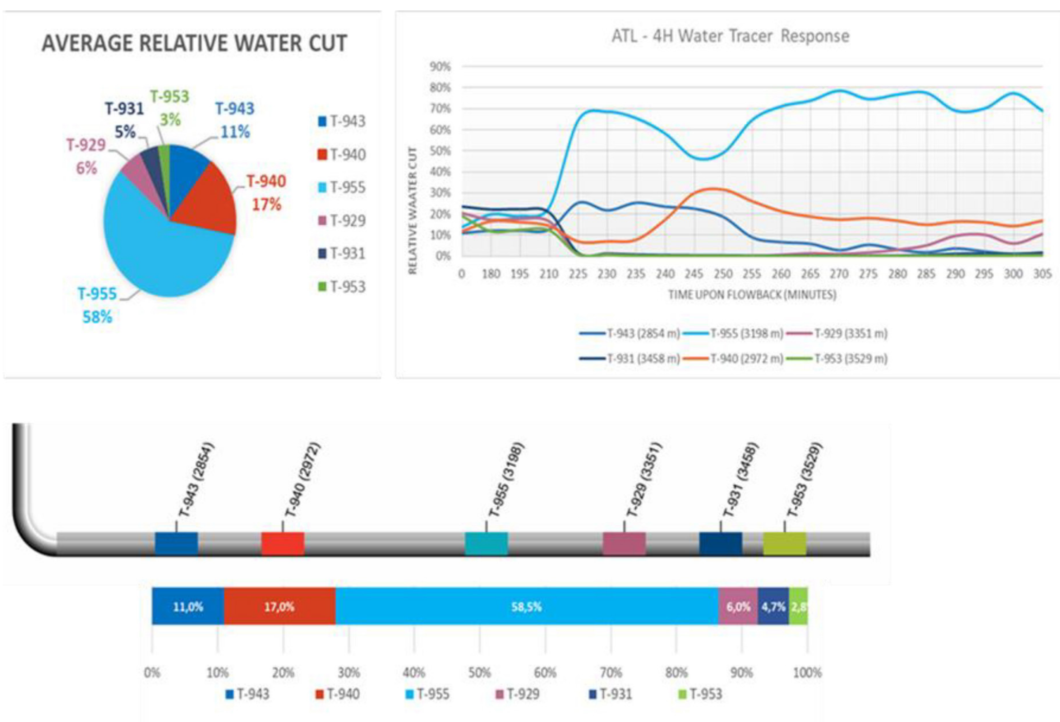

Figure 31. Water tracer analysis (sampling of clean out flow).

Although very little water was present it was possible to extract adequate water for analysis from the Clean Out, 2nd, 3rd and 4th flow tests. Following initial clean out, the 2nd to the 4th flow showed a reasonable balance of water cut along the well when compared to the first two wells due to the use of AICDs, but there was an increase in water cut over time in the Toe region, mainly in the region of the T-931 tracer (3458 m) which can be clearly seen in figure 32 below:

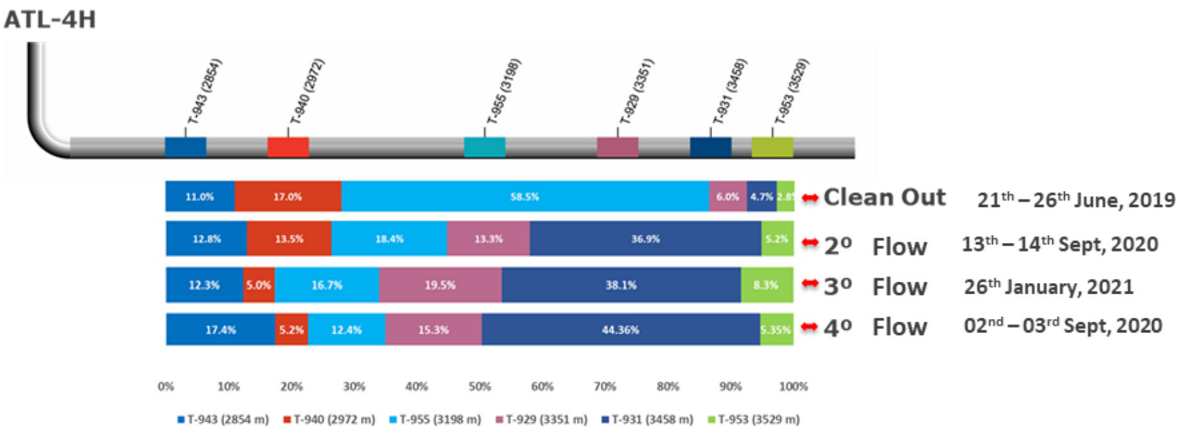

Figure 32. Relative percentage contribution by water tracer for each flow studied.

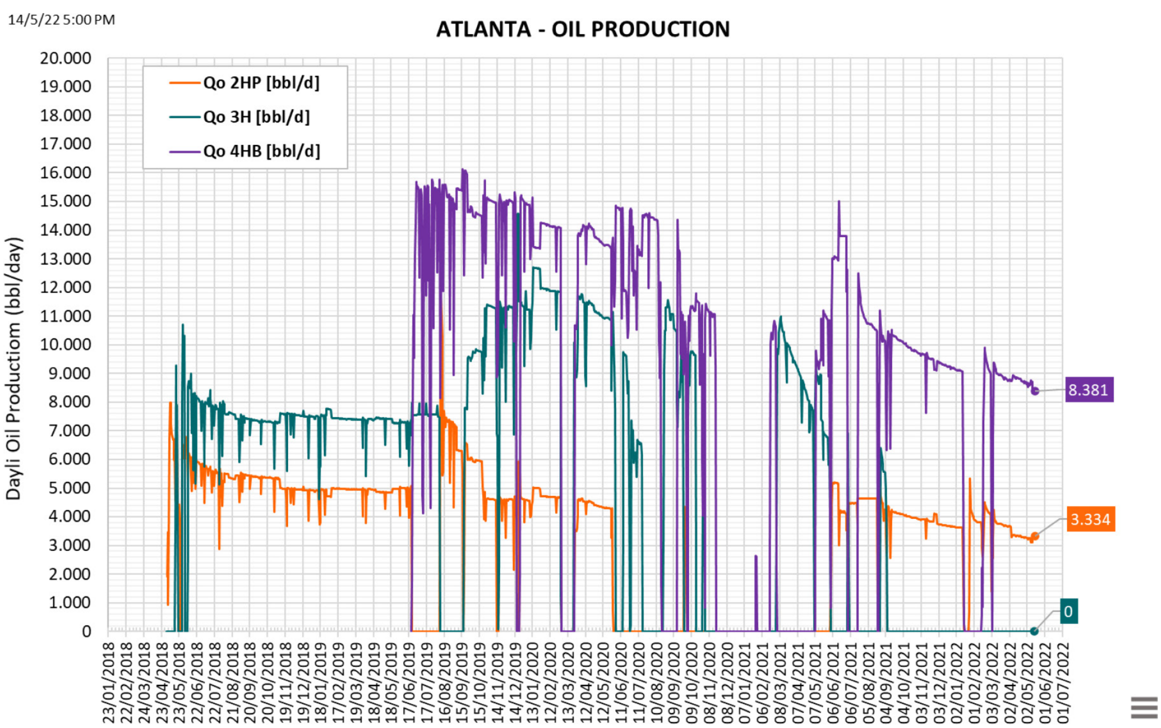

Figure 33. Oil production of 3 Atlanta wells.

PRODUCTIVITY AND WATER PRODUCTION FINAL ANALYSIS

The third producing well, ATL-4, began production in June 2019 above expected rates, confirming the effectiveness of the design. With the available data, no negative impact due to well design and completion was seen in production. By contrary, this is the most prolific well, amongst the 3 wells planned for the EPS, producing at a maximum rate, limited by ESP capacity (Figure 33).

Also, water production of the well is the lowest in the field (Figure 34). This behavior can be partially explained by the geological configuration of the well and the aquifer, but the results are in line with the AICD flux uniformity and water restriction.

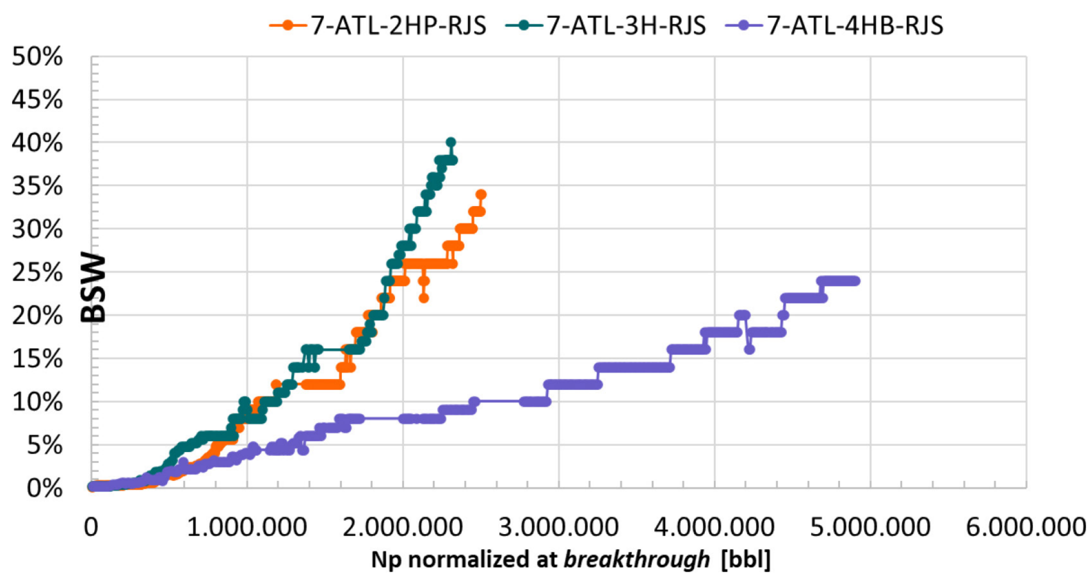

Figure 34. Water production of the wells.

CONCLUSIONS

Tracers proved to be a considerable efficient evaluation method with no additional intervention needs, compatible with Hz–OHGP nd AICD use, providing the following information:

- Confirmed effective packing across the full length of the horizontal.
- Showed an equalized flow along the well caused by the water inflow restriction from use of AICD's located at the heel.
- As the water cut increased, the tracers showed a considerable increase in the oil production of the Heel-Mid zone in detriment to the Mid-Toe zone.

- The water tracer results across the multiple measurement campaigns showed a strong increase in the water ingress around the position of tracer T-931 (water - 3458 m), increasing the actuation of the AICDs and restricting the fluid inflow around those positions. On the last campaign performed, the level of restriction was so significant that tracer T-701 placed at this location (oil - 3423 m) was not detected.

NOMENCLATURE

AICD	=	Autonomous Inflow Control Device
BHA	=	Bottom Hole Assembly
BOPD	=	Barrels of Oil Per Day
BSW	=	Basic Sediment and Water
DPS	=	Definitive Production System
EPS	=	Early Production System
ESP	=	Electrical Submersible Pump
FPSO	=	Floating, Production, Storage and Offloading
GP	=	Gravel Pack
Hz-OHGP	=	Horizontal Open Hole Gravel Pack
ICD	=	Inflow Control Device
LCM	=	Lost Control Material
LWP	=	Light weight proppant
MD	=	Measured Depth
OWC	=	Oil/Water Contact
TVD	=	True Vertical Depth

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