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CHICHIMENE FIELD T2 SAND: A SUCCESSFUL APPLICATION OF CYCLES IN A WATER INJECTION PROJECT ON HEAVY CRUDE OIL, ENABLED BY A NOVEL SMART SELECTIVE COMPLETION SYSTEM ADAPTED FOR WATER INJECTION.

CAMPO CHICHIMENE ARENA T2: UNA EXITOSA APLICACIÓN DE CICLOS EN UN PROYECTO DE INYECCIÓN DE AGUA EN CRUDO PESADO, HABILITADA POR UN NOVEDOSO COMPLETAMIENTO SELECTIVO INTELIGENTE ADAPTADO PARA LA INYECCIÓN DE AGUA.

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ABSTRACT

This paper presents the application of injection in cycles, assisted by the first smart selective completion system with remote valve operation. The completion system was installed in the Chichimene Field unit T2 (Fm. San Fernando). The results were compared with conventional water injection, technology that utilizes a simple selective completion system, for recovery factor, water consumption, operation style, and others.

The target unit has been subjected to selective water injection since 2016. This process consisted in injection of a controlled amount of water within 3-4 zones in equilibrium with the extractive system on producers wells to find a better crude oil movement and a commercial recovery factor. Nevertheless, the surveillance evidence suggests that some zones consume too much water due to its high permeability (heterogeneity), which affects high water cut on producers (due to the adverse mobility ratio), but also suggests that there is a better way to further improve the recovery factor. This enhancement was enabled with a smart selective completion system by promoting a scheduled temporal closure of zones while production continues, having achieved pressure-production restoration effects on the closed zones, resulting in an efficiency increase of the vertical and areal sweep.

To determine if this could work, a smart completion system was installed in one well in August 2019. For more than one year, the operation and interpretation of the DAS measuring tool (Continuous sound recording) was understood, from which injected water per zone is known daily; thus the optimization of the injection rate per zone improved the production pattern behaviour. In February 2021, the injection cycles started on the well by zone, and to date, more than 25 monthly cycles have been completed, increasing the recovery factor, with a considerable reduction in water and energy consumption, maintaining a continuous measurement of zone injection. Thislevel of information has never been reached in the industry.

The case study establishes a new frontier related to selective injection and also in cycles, an evolution step in water injection technology. This pilot combined in a single design selective injection, intelligent remote operating completions, continuous layer injection measuring by DAS, extra heavy oil WF, and management of high permeability variations. It is aligned with the latest regulations on decarbonization (water and energy saving). From a reservoir point of view, there has never been monitoring in injectors with this level of quality to enhance performance; in addition,, on the surface this technology has translated into a significant reduction in the use of wirelines for well operations, and has improved some well cleaning interventions with coiled tubing.

KEYWORDS / PALABRAS CLAVE

Waterflooding: Intelligent completion | Cycle injection | Advance water injection | Selective injection | Heavy oil waterflooding.
Inyección de agua | Completamiento inteligente | Inyección Cíclica | Inyección de agua Avanzada | Recobro crudo pesado.

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RESUMEN

Este trabajo presenta la aplicación de inyección en ciclos, asistido por el primer completamiento selectivo inteligente con operación remota de válvulas. El completamiento fue instalado en el Campo Chichimene en la unidad T2 (Fm. San Fernando). Los resultados han sido comparados con la inyección de agua convencional que se realiza con completamiento selectivo sencillo, en los aspectos de factor de recobro, consumo de agua, estilo de operación, entre otros. La unidad objetivo ha estado sometida a inyección de agua selectiva desde 2016, cuyo proceso ha consistido en inyectar por 3-4 zonas una cantidad de agua controlada en equilibrio con el sistema extractivo en pozos productores para buscar un mejor desplazamiento de crudo y un factor de recobro comercial. Aun con esta estrategia, en el proceso se evidenciaron posibilidades de mejora, algunas zonas consumen mucha agua debido a la alta permeabilidad por la heterogeneidad de la roca, y está agua impacta en un alto corte de agua en los pozos productores, debido a la relación adversa de movilidades en el yacimiento. Con el completamiento selectivo inteligente se activa esta posibilidad, al permitir con un cronograma el cierre temporal de zonas mientras se continúa produciendo, logrando efectos de restauración de presión-producción en las zonas cerradas, permitiendo incrementar la eficiencia de barrido vertical y areal.

Para determinar si esto puede funcionar, el completamiento inteligente fue instalado en un pozo en agosto de 2019. Durante un poco más de un año se comprendió su funcionamiento e interpretación con la medición DAS (Registro continuo de sonido), con la cual se obtiene el valor diario de agua inyectada por zona, la sola optimización del punto de arranque permitió mejorar el comportamiento de producción en el patrón. En febrero de 2021, se iniciaron los ciclos de inyección en ese pozo y a la fecha se han realizado más de 25 ciclos, incrementando el factor de recobro, con una considerable reducción en el consumo de agua y de energía, manteniendo una medición continua de inyección por capa, no alcanzada previamente en la industria.

El caso de estudio establece una nueva frontera en la materia de inyección selectiva y en ciclos, permitiendo una evolución de la tecnología de inyección de agua. Este piloto combinó en un solo diseño: inyección selectiva, sartas de inyección operadas remotamente, medición continua de inyección continua por capas con DAS, recobro en crudos extrapesados con inyección de agua, manejo de severas variaciones de permeabilidad y se encuentra alineada con las nuevas regulaciones de descarbonización. Desde el punto de vista de reservorio, nunca se tuvo un monitoreo en inyectores con este nivel de calidad para mejorar el desempeño y en superficie, esta tecnología ha permitido reducir en forma importante el uso de cables para operaciones en pozo, así como mejorado las operaciones de limpieza con coiled tubing.

1. INTRODUCTION

The oil industry has performed water injection for nearly 100 years. This has been conducted using different techniques and styles that have allowed to incorporate it as an almost symbiotic part of most of the developments worldwide; for instance, water injection in flank, patterns, lines or combinations thereof. The patterns have been designed in multiple ways,; over time, injection evolved from commingled to selective injection. Incertain fields, they applied this selectivity by placing exclusive injectors in each level [i], in the 90's the selective completions generated a disruption in the industry. Countries like Argentina, adopt them in all their designs. In that decade, electro-submersible pumps also appeared, which create extractive conditions not previously observed in high permeability reservoirs or in fields operated with multiple sands at the same time, thus achieving better productivity in operations with injection. Measurement technologies also evolved, where pressure changed from analogue to electronic measurement with the formation tester; then, continuous test sensors became fashionable when they started to be lowered into completion pockets, replacing the log with the nitrogen pump that detected the flow level. Expensive data started to be more reasonably priced, and there was mor openness as for access to information. . The way in which data flow is interpreted also changes, but not only in relation with measurement but also for analysis. Disruptive software is leading the industry, changing the way we analyze production and geology, and numerical simulators allow us to better understand reservoir behaviour.

Between 1990-2010, new techniques such as interspaced wells, injectors rotation, cycle injection, selectivity completion, emerged in the industry as a need to improve the recovery factor (RF), and the efficiency of water injection projects already developed, or even new ones. In this period, the selective injection combined with the high-capacity production equipment and the beginning of the era of continuous measuring by downhole sensors in producing wells, results in the revitalisation of old fields (Massaglia et al, 2006). With respect to data management, an important development arose regarding information availability based on sporadic to daily data samples.

Over the last decade, IOT has made it possible to install state-of-the-art mechanical equipment with new computational capabilities in surface and downhole facilities, creating an additional possibility to optimize or implement new practices. Considering these possibilities, an adaptation of a high-tech industrial completion system, which was originally intended for production wells, was adapted for injection wells, see figure 1.

These technology capabilities already tested in several producer wells in complex fields were combined with the natural geological – dynamical case of Chichimene T2 sand to test the mechanism of cycle injection, but under unprecedented operating conditions. The fabricant was to be evolved to reach this target, (Sanchez et al, 2021; Satti et al, 2020).

The field test conducted since 2019 to present has been successful in its planning, execution, and results, allowing new possibilities for development of the basin. The level reached could represent a third period in the history of water injection, one with a digital role and remote operation, more adapted to reservoir realities. This paper describes this test from its design phase, through aspects of the operation, and the results achieved to date.

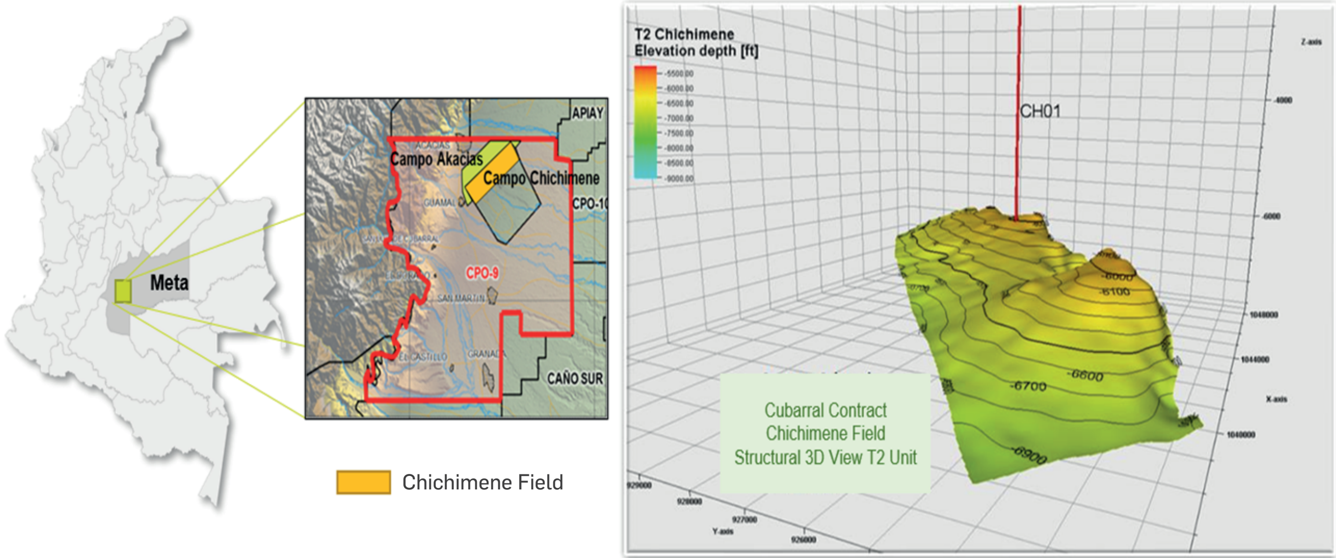


Figure 1. Location of the pilot area (left) - Structural view of the reservoir (right). Source: Ecopetrol database.

2. THEORICAL FRAMEWORK

BACKGROUND IN WATER INJECTION CHICHIMENE FIELD.

A) FIELD GEOLOGY.

The Chichimene field is formed by a monoclinal structure in the lifted block, dipping to the NW with two main crests to the north and south, and a structural low or valley in the central area (refer to figure 1). No important faults are identified internally, with exception of the main fault system that limits the structure from the southeast, separating it from the lower block which apparently corresponds to the side of Castilla's structure.

As for the reservoir, the total thickness varies from about 250' in the fault zone to about 350' on the limits of the block. This vertical column has massive sand deposits interbedded with thin clay layers that correspond to local flooding surfaces, which, with a few exceptions, are rather discontinuous (see Figure 2).

Despite the massive presence of sand layers, it is a situation of high heterogeneity, (figure 3 highlights this characteristic). In general, the reservoir is highly permeable, with reservoir type rocks ranging between 10 mD and 10 to 20 D, which generates zones of notably different flow capacity, a rather unfavourable contrast for an optimal injection vertical profile (Solórzano et al, 2018).

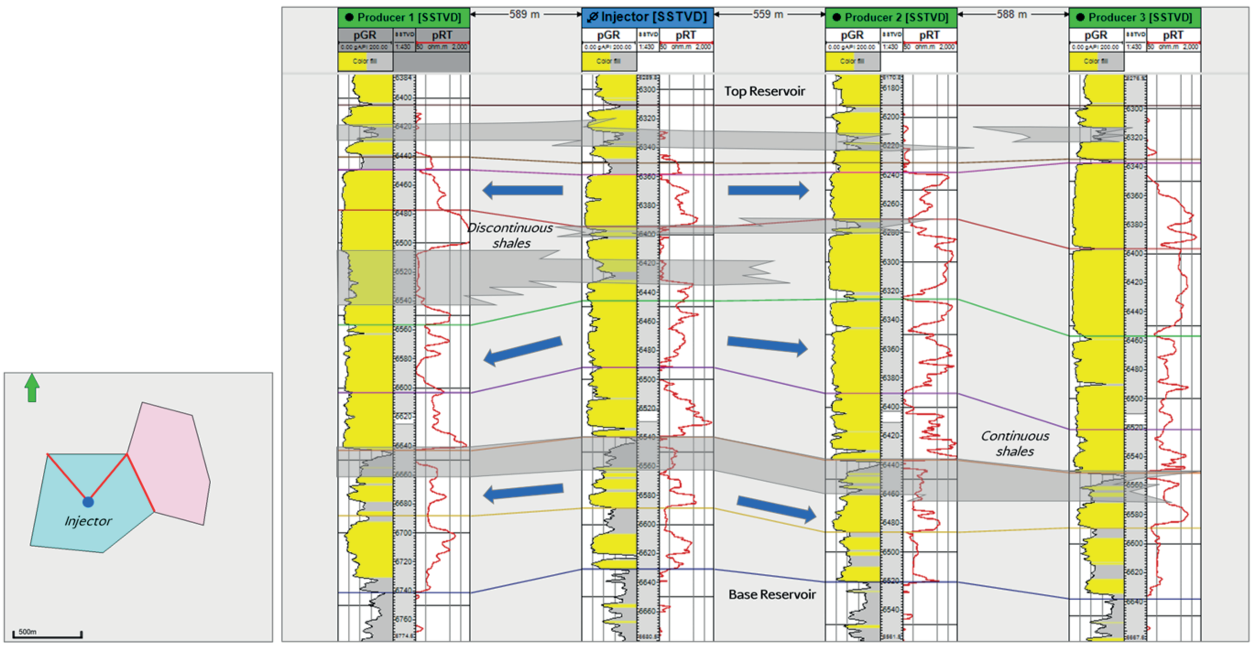


Figure 2. Typical geological section of the reservoir. Source: Ecopetrol database.

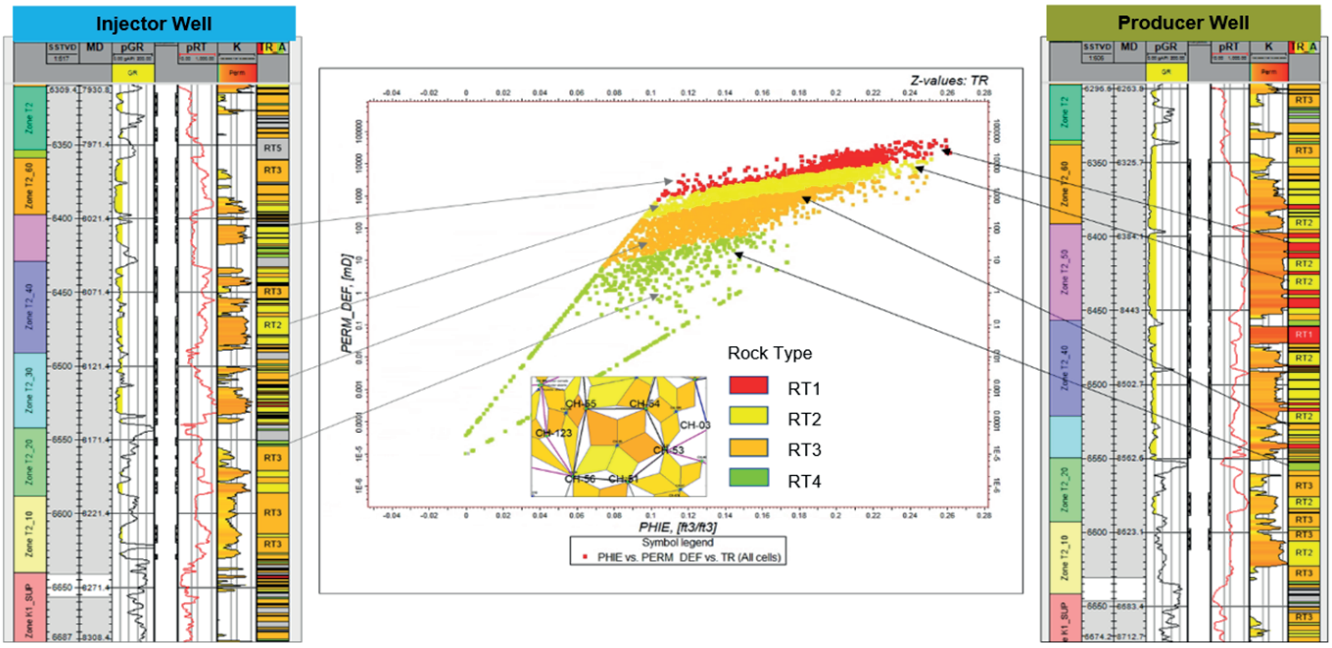


Figure 3. Observation of the contrast of porosity and permeability in the reservoir despite the homogeneity of the GR. Source: Ecopetrol database.

B) APPLICATION OF THE CONVENTIONAL COMPLETION SYSTEM.

In the reservoir, the conventional completion system was applied to injector wells, which consisted in perforating about 200' of reservoir sand and the placement of tubing with packing at the top of the intervals of interest. This test was performed from 2015-2016, without achieving the most ideal results, see figure 4 (left). The injected water flowed at high rates through the super high permeability channels generating noticeable water breakthrough on the producing wells in only a few weeks (50-80%); thus, it was determined that the previously described completion system should never be used again, and it was replaced by a selective string (Solórzano et al, 2018), see figure 4 (right).

C) APPLICATION OF THE SELECTIVE COMPLETION SYSTEM.

Since 2016, the installation of conventional selective completion systems was performed to stabilize in the most suitable manner the injection flow rates in vertical intervals. Between 3 and 5 zones were chosen in each well, guided by the natural flooding surfaces (shales that act as effective flow seals beyond completion). Thus, the vertical distribution was enhanced and, therefore, this allowed a massive project expansion throughout the whole field, see figure 4 (right).

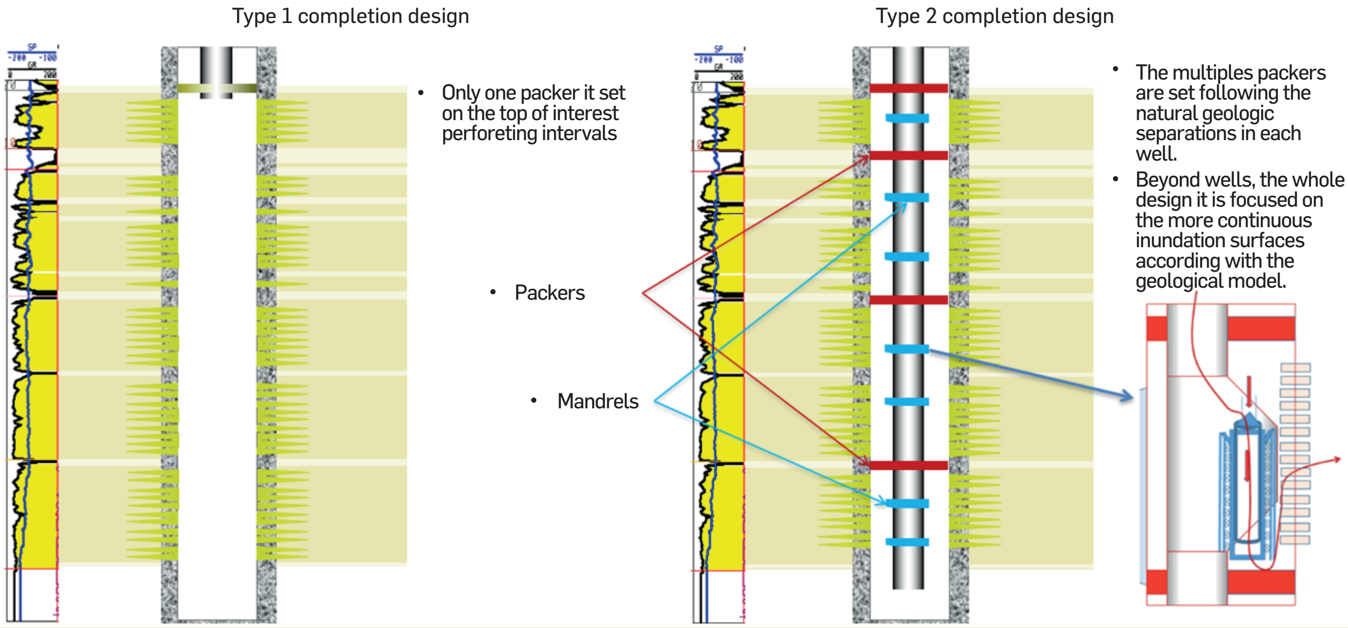


Figure 4. Completion systems tested and used in the field prior to application of the smart completion system prototype. Commingled completion system injector (Left) – Conventional selective completion system injector (Right). Source: Ecopetrol database (Solórzano et al, 2018).

LIMITATIONS OF THE SELECTIVE COMPLETION SYSTEM APPLIED OVER THE T2 SAND.

The conventional selective completion system had allowed to notably increase the RF of the field, but this tuning was achieved by constantly regulating up and down the valves in each zone. In some cases this regulation requires more than one intervention and, given the permeability contrasts, several times a year, also requiring a large monitoring team. This situation is related to the combination of heavy crude oil (viscosity) and high permeability contrast; the effect is the increased difficulty to find stable operating flow rates. Nonetheless, the RF rendered remarkably better results as compared to not performing WF in the field. Included below are some discussions on performance.

I. THE HEAVY CRUDE OIL PROBLEM (VISCOSITY):

The crude oil viscosity lies between 300 to 700 cps upon the reservoir zone and the water is 0.5 cps approximately. TThe reservoir temperature is 200 to 220 °F, and the water heats up when it arrives to reservoir, thus helping the displacement process, as the oil is very sensitive to heat. The mobility ratio has been estimated at 18.648, almost 4 times the best recommended for WF. To help this process work better, the operation team works at the field with and extended delta P permitted by low flowing pressures between injectors and producers. Flowing pressures are about 2200 psi on formation in injectors and about 600 psi on formation on producers, which means that the difference is about 1600 psi. This technical issue allows crude oil to be "pulled over" from the formation, from the producers, with water pushed behind, so that the net effect is a field acceptable ratio between water injected and oil produced. Such ratio, has been "5 IWB/STB" over the 9 years of the project, which is a fantastic result (Solórzano et al, 2018).

II. THE HIGH PERMEABILITY CONTRAST PROBLEM:

In figure 3 (K track), it can be observed that the permeability lies between 10 and 10000 mD or even more. This situation produces a Dystra Parson coefficient of V=0.97; observing the reservoir gross thickness, this factor reduces to V=0.78; if observing only a "selective zone" space, or even greater to a V=0.5, you can only think of a clean sand zone. The selective completion improves the behaviour of the WF by cracking the high V (all T2), in various medium behaviour V (zoning T2) (Solórzano et al, 2018).

If you observe a geological subunit in figure 3, it can be noticed that more than one flow unit is established (rock type track), where RT1 are flow highways and zone sectors; some wells contain much RT1 or RT2 massive, permitting better water flow as compared with other zones, which is not always good.

III. THE OVERALL BEHAVIOUR:

In the scenario of successful operation of the water injection currently installed in the field, what happens within the thickness of each injection zone? The answer is: There still are important permeability contrasts as these variations occur every few feet (see figure 3). For a column of more than 300' thickness, which is just mechanically separated in intervals of 40-80' (upon each well); therefore, only a reachable, limited RF, would be related to the internal inefficiency of each 40' to 80' zone in each well.

Consequently, the Chichimene field's installed selective WF still leaves large volumes of crude oil without being contacted or displaced. Within the method implementation, internal channelling still occurs; therefore, the WF WOR would be high and since its impact on the opex is a reality, the overall effect would limit the RF because of profitability reasons; see figure 5 (an imaginary path of internal reservoir WF behaviour).

ARRIVAL OF SMART COMPLETION TECHNOLOGY.

In recent years, well completion technology has evolved significantly to the point that today, several suppliers in the market have completion systems with capacities to produce or inject several reservoirs with differentiated regulation. These systems range from those that are regulated with the wireline intervention of a coiled tubing unit in the well, to those that are regulated by electric or electrohydraulic commands from the surface or beyond, from

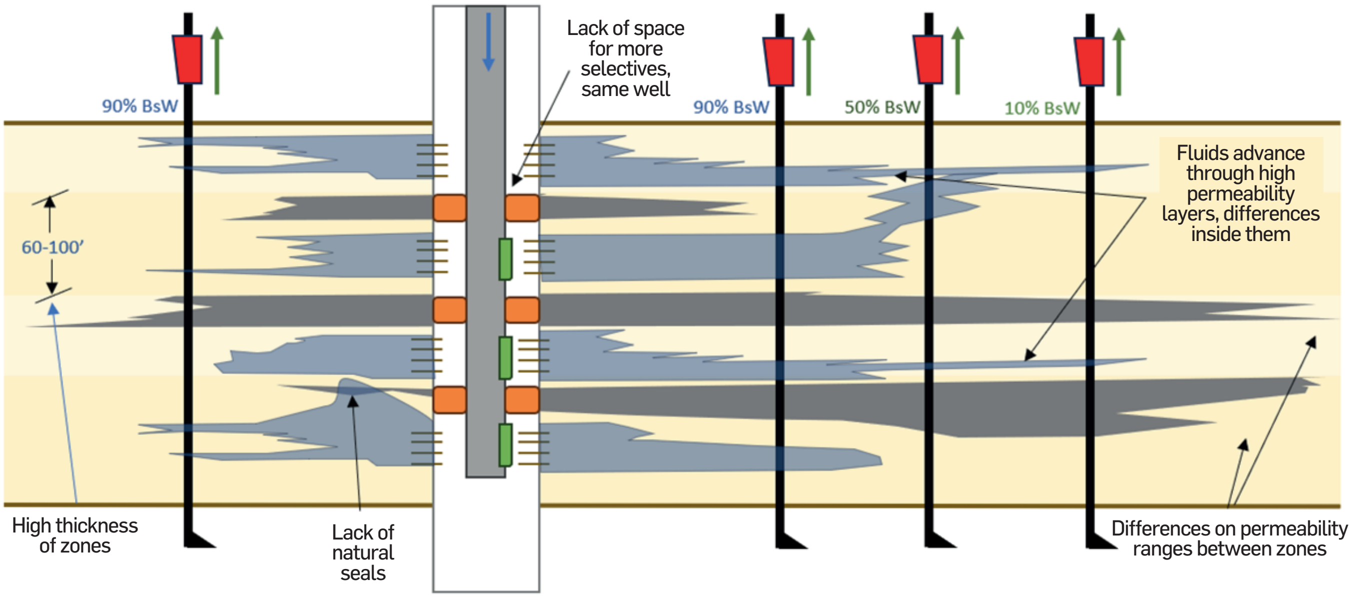


Figure 5. Highlighting the inefficiencies of selective injection process. Source: The authors

remote locations using internet (Costa et al, 2017; Dyer & Bouldin, 2016; Ross, 2022; Joubran, 2020; Bellaci et al, 2015; Wilson, 2018, Nguyen et al, 2019; Samuel et al, 2023). The first in the world to be installed as an injector, was the one named herein.

The advantages (within the context of water injection) provided by this equipment are highlighted below:

- Configurable according to the wells and reservoir needs.
- They have remote operation (either from wells surface setting box, or from a real time operation centre, or from internet command set) for some of their different configurations. (The well on this study had been operated from a surface box and from an internet command set (Sanchez et al, 2021)).
- They have new generation tools to measure: pressure, temperature, noise, production, or injection.
- They can have selectivity in multiple zones as needed.
- In the selective tolls, it can be regulated to the flow rates.

The combination of these factors set an evolutionary leap in the concept of water injection. The new generation of completions allows operators to set selective injection oscillations or even just better flow adjustment (note selective by zones), without repetitive interventions with wirelines or coiled tubing in wells to change valves, as was the case in the past.

With the pilot in Chichimene field, it was observed that this type of completion has permitted to improve the intrinsic control of injected volume per zone without further action. As a conclusion, the technology upgrade operation permits the cycles to operate in a much more automated way, thus making available an additional recovery factor over the traditional selective WF.

Also, a significative plus is the rise in density of injection and production data, the possibility of automated digitalization of this information through the cloud, which could even be in timeframes of minutes or seconds. , Part of this is showed further ahead with the DAS log upgrades (Sanches et al, 2021), facts that would allow enhancing operation quality levels never reached before.

3. STATE OF THE TECHNIQUE

BACKGROUND IN INJECTION IN CYCLES.

Cycled injection is not a new concept in the industry. It, has been tested in several fields worldwide, including tests in 1960 in Spraberry and McCamey in Texas, as well as in the Skaggs field in New Mexico, both in the US; it was also tested in Jablonev Ovrag and Kalinovskoye in Russia. In these fields, the methodology was tested using conventional completions, and the concept applied was the shut in of the injector well for a certain time. Resulting from these attempts, additional recovery factors are 5-11%, and that the greatest effectiveness derived from conditions of greater contrast of permeability or heterogeneity (Sharbatova et al, 1985).

In 2003, in the PPT field in Germany, the technique of pulses and no cycles was applied, which consists in the generation of assisted downhole pressure to create vibration in the injection water. This is similar to that called "rocking" in operations conducted for admission in wells under stimulation (Groenenboom et al, 2003).

In 2008, Shchipanov et al. emphasizes: "pulsed water injection lies in the control of well activity, i.e., it controls the pressure distribution between an injector well and a producer well causing a flow channel that allows sweeping zones that in traditional water injection remain untouched". In this work they report the study of cyclic injection in heterogeneous sand fields of the North Sea with success, where recovery factors between 3 and 5% were reported in the study (Shchipanov et al, 2008).

During the years 2010-2014 in the Las Mesetas field, GSJB, Argentina (Perez et al, 2014), the methodology was reviewed. In this case, Pérez et al. highlights that in these areas, it had been observed that when an injector is shut in, it would not always result in an immediate decline in oil production. In these fields, the application was applied with zone shut in within the selective string wireline enabled, which is commonly used in this basin due to its geological characteristics. The authors report a complete simulation study adapted to the study area. The studies suggest that that even in the absence of capillary movements, the cycles are successful in improving the vertical and areal efficiencies.

In 2014, a thesis from the Norwegian Institute of Science and Technology reports a simulation study applied to the understanding of this concept. As a conclusion of this monography: Subjects as reservoir pressure, cycle injection period, injection flow rate, reservoir thickness, rock wettability and permeability distribution, vertical transmissibility, cycle activation time, and age of the patterns in previous injection, are the most representative parameters that affect the cycle injection results. The study shows RF between 2-20% depending on the combination of these parameters (Langdalen, 2014).

In 2016, studies reported cyclic injection in fractured shale – tight rock cores. This study highlights the importance of injection pressure during the pulses, as the higher the pressure, the higher the RF. Nevertheless, this study was more focused on shale type sands interbedded with conventional sands, but conceptually shows the benefits of generating oscillation in the injection to compensate the channelling (Yu & Sheng, 2016).

In 2020, modern attempts are reported in the Hoople field, in Midland, Texas, USA, the project consisted of generate a reservoir injection rotation by shutting in several injectors simultaneously in complete field sectors, a case more like big reservoir sectors cycle injection; all the areas where the method was applied, showed decay of decline and even production increase in producer wells. In the public report, this field does not indicate the application of selective strings but rather the closing and opening of complete wells (Farias & Liu, 2022).

In 2018 Ecopetrol. S.A. started planning the injection cycles in the Chichimene Field (Lopez & Uricochea, 2019), enabled by a smart selective string; this trial, which effectively started in 2020, allowed the application of injection oscillations at different reservoir levels without shutdown of the producing well and without mechanical interventions to change valves regulation, a whole new method, first ever of its kind.

Many other cases are recurrent in the industry, so the cycle injection is a well proven technique with efficacy in increasing the RF; in short, the accumulated knowledge of this art can be concluded as:

- The use of pulses and/or the use of cycles allows the RF to be increased; reports with information on this number range from 2 to 11%.

- Cycling in fields without selective string involves complete shut in of the injector well, creating loss of operational continuity.
- The application of cycling in fields with conventional selective string involves the use of wireline equipment to constantly calibrate valves by blinds on a repetitive basis every month, which results in a very significant opex cost, as well as the high risk of leaving material in the wells. With the smart selective string, this well service is replaced by digital services for a better well operation handling and information extraction.
- Cycles are more efficient in reservoirs with higher permeability and/or viscosity contrast between different reservoir zones and higher thickness.

4. EXPERIMENTAL DEVELOPMENT

CYCLE INJECTION PILOT DESIGN.

The cycle injection pilot was planned to consider factors like the appropriate pattern to start, mechanical condition of the injector well, oscillation (cycles) strategy in the reservoir, adding up the design of a completion system capable of performing the required tasks in the reservoir planned process and expansion possibility.

A) INJECTION PATTERN SELECTION.
Understanding the factors that inspired to continue developing a better technology to enhance the RF, a new intelligent completion system was designed for a pattern that had been injected before with a conventional and a selective completion, see figure 4. A new standard was designed in the same injector to observe evolution trends referred prior injection results.

The change, if compared from previous selective completions, would combine application of a better vertical water distribution but also with the ad of injection cycles in the same reservoir system, see figure 6. The whole new process is permitting a new level of recovery efficiency and is successfully combining technology (intelligent string completion) and methodology (cycles injection).

B) CYCLE INJECTION PLANNING.
The cycle injection schedule, from a technical standpoint based on referenced simulations, requires operational expertise in the comprehension of the injection pattern behaviour (surveillance team, subsurface equipment, and reservoir behaviour and the limitation of the equipment itself - hydraulic combinations). A novel well cycles injection plan was generated in this pilot to start field test and understand the behaviour,. This plan was used to follow the capacity of the operation team to perform this kind of job that requires several actions in the injector well, see figure 7.

The injection in cycles can be thought as a number with hundreds of combinations of flow rate from cero to maximum rate per reservoir zone (upon equipment capacity and permeability). Usually, the solution requires shut in and open each sector at different times promoting that the well never be shut in. Total injection should always be more than the minimum surface operational rate, but it can also be zero if the other rate is not possible.

EXECUTION OF THE INJECTION PILOT IN CYCLES.

The prototype well was composed of 4 zones, (alternation zones:

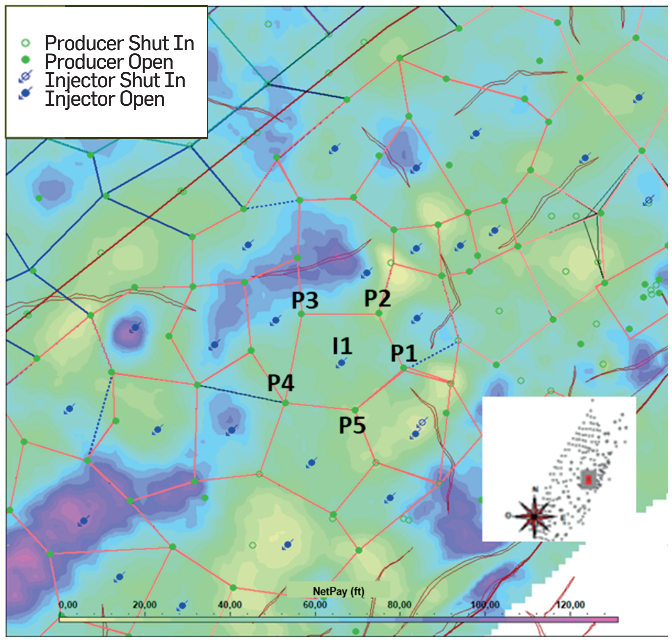


Figure 6. Design and location of the prototype pattern for testing. Source: Ecopetrol database.

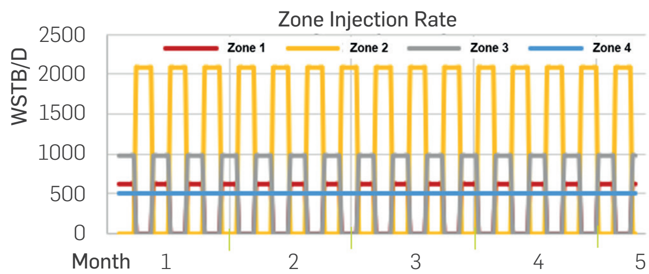


Figure 7. Cycle injection planning, prototype well. Source: Ecopetrol database.

1 to 4, deeper to shallower)., The project team defined to keep zone 4 permanently opened (caused by its lowest historical admission), as well as the opening and closing cycles were combined, leaving open for 21 days zones 2 and 4, and for further 21 days zones 1, 3 and 4, see figures 7 and 8.

A) COMPLETION SYSTEM INSTALLED IN THE PROTOTYPE WELL – BOTTOM.
In the prototype well, a completion system composing of 4 zones was installed, with fiber optic equipment and configurable receiver in DAS and DTS options. After the initial operation analysis, it was decided to continue using DAS as a monitoring mechanism. This completion system was installed within a 7" casing, and each zone has an electric valve with 6 choke positions.

B) COMPLETION TECHNOLOGY INSTALLED IN THE WELL – SURFACE - BOTTOM OPERATION SYSTEM.
On the surface, an automated control unit box was installed, which has the capacity to operate subsurface valves and the general system from the well and even transmit protocols information through a satellite data transmission card or cable web, it additionally can receive commands remotely (IOT-Cloud technology). For the pilot

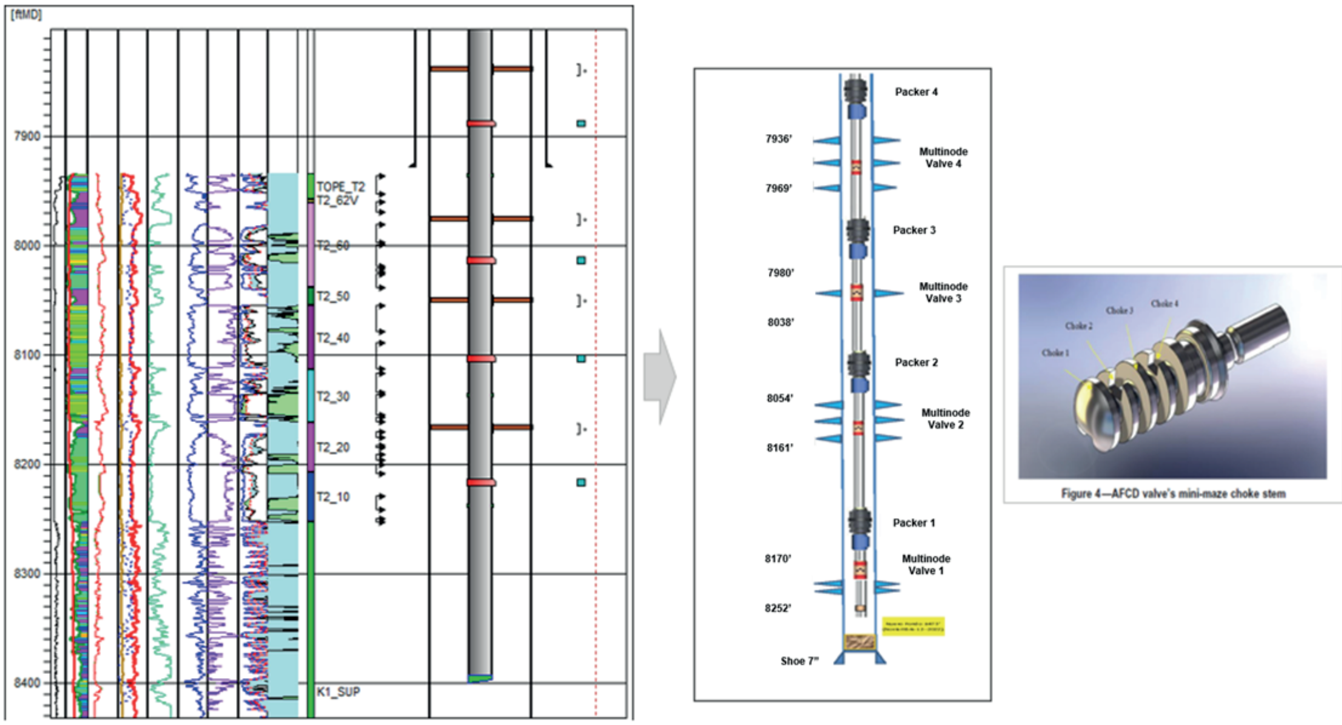


Figure 8. Completion used in the prototype well (left), example of valve in each zone (right). Source: Ecopetrol database, the valve picture is an image property of Baker (Jacob et al, 2018).

case, the prototype well works under a contract of technological trial with the product provider (in testing phase), see figure 9 (Sanchez et al, 2021).

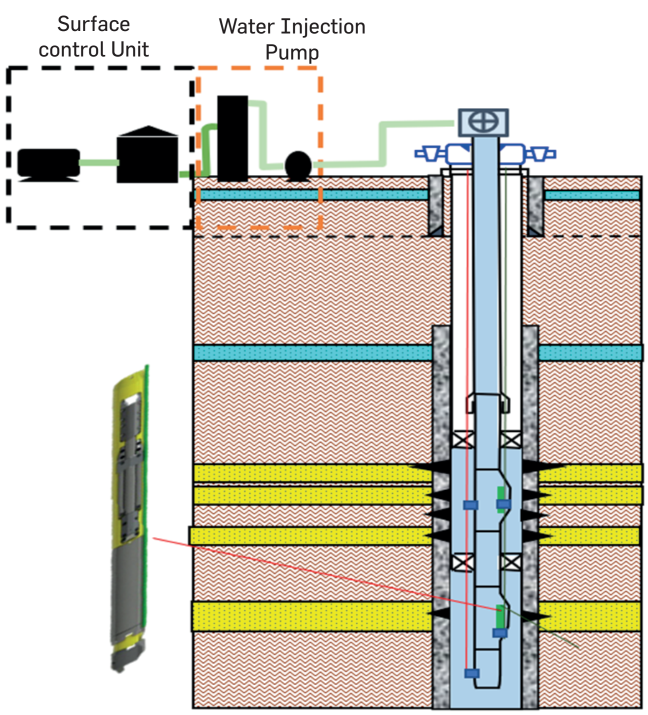
The bottom valves are triggered by an electric mechanism that allows movement through 6 positions for the adjustment of the desired flow rate. An optic fiber cable is installed in the whole well and continuously collects information in the arrangement regarding the data capture mode. This tool is capable of measuring temperature (DTS mode) or noise (DAS mode).

For the DAS case, the tool measures deformation of the fiber using a laser signal emission, like a sound membrane, this measurement is transformed into wavelets that compared along the well column with the completion system of the well, allow understanding the qualitative aspects of the injection (sound and rates are related variables), and after rigorous mathematical processing, quantitative values regarding the distribution are acquired.

C) CALIBRATION PERIOD DAS - ILT.

With the pilot well operating, and being the first of its kind, wireline ILT runs were performed (using a wireline supported DTS type tool), and injection information was obtained in a traditional way, in parallel with the continuous measuring with continuous DAS information and then, the mathematical analysis that leads to the injection allocation was performed. Both records were compared, and the following observations were obtained (Sanchez et al, 2021):

- DAS allows observing the injection evolution minute by minute, an ILT is normally run once every 3 months to a year (top field) and by 6 months or annually (marginal fields), according to the decision of monitoring operators, see figure 10.
- Closings and openings were performed with DAS observing



Source: Baker Hughes and Schlumberger

Figure 9. Completion system used in the prototype well (Sanchez et al, 2021).

its correspondence with the valve's mechanical operation information, see Figure 11.

- The ILT tool produces noise and interference in the well throughout the run, this interference affects the injection allocation comparison, but it generally doesn't have a noticeable impact, see figure 11.
- The conventional ILT tools are not capable of detecting low flow rates, which in contrast can be observed through DAS: throughout all tests of this kind, the well determined that DAS has better sensitivity, see figure 11.
- For the first time in the industry, a specialized tool shows the injection oscillations within the well depth over time, it could almost be said that in real time. In the example of figure 10 you can observe different valves configuration in large periods (up) but also the effect at the moments of valves calibration (bottom).

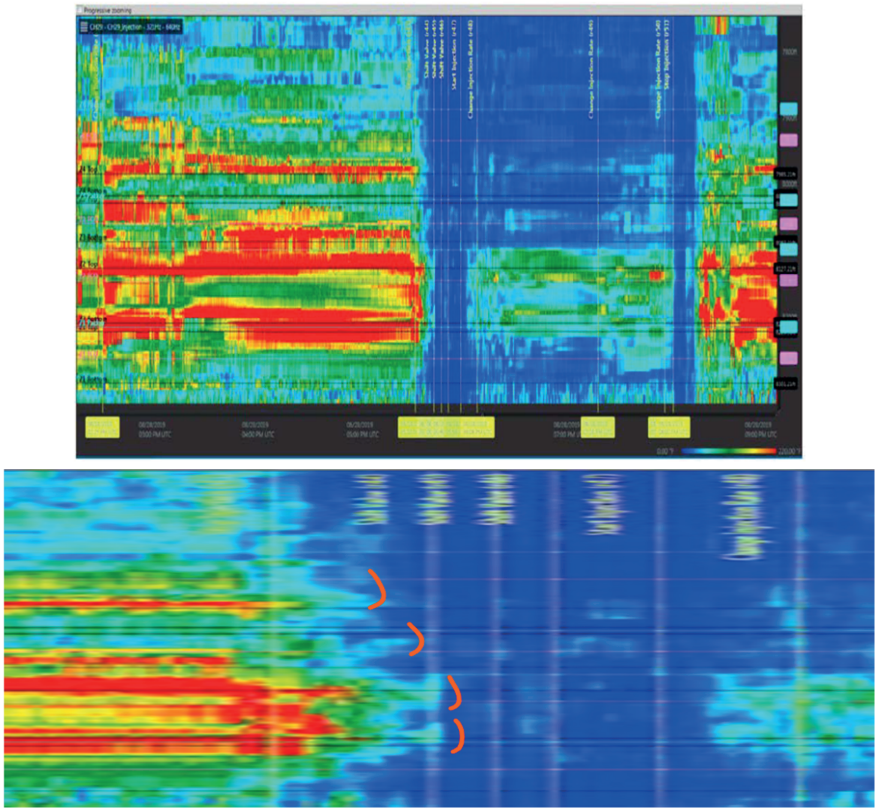
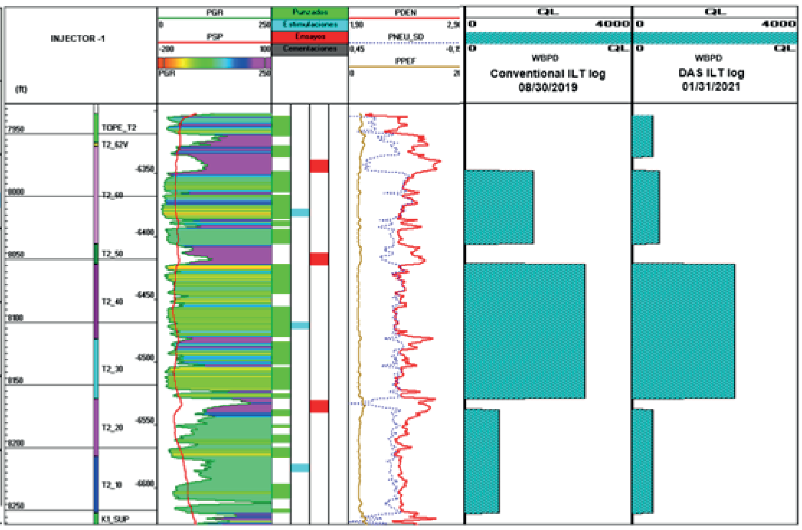


Figure 10. Observation of the sound measurement over time in the prototype well, top view of several days; below, zoom during operation of the boreholes (Sanchez et al, 2021).

d) Application of cycles.

When it was considered that the well and the equipment were correctly configured in terms of mechanics, electronics and interpretation protocols of DAS, the period of cycles was initiated, using the planned information, approximately every 21 days the valves are operated changing the injection condition of the well. This activity continues daily with injection flow rates per zone; figure 12, shows a summary of the injection in a 10-month period, and also shows the clean behaviour of the sound wavelets with zone changes (Satti et al, 2020).

Test Number	Date	Choque position	ILT (Allocation)	ILT WBPD	DAS (Allocation)	DAS WBPD	DAS vs ILT (%)
1	6/08/2019	Valve Zone 4	0%	0	5%	266	-5%
		Valve Zone 3	20%	1190	11%	631	9%
		Valve Zone 2	71%	4262	68%	3994	3%
		Valve Zone 1	9%	548	17%	1009	-8%
2	23/08/2019	Valve Zone 4	0%	0	11%	599	-11%
		Valve Zone 3	30%	1598	20%	1055	10%
		Valve Zone 2	59%	3117	40%	2136	19%
		Valve Zone 1	11%	585	28%	1505	-17%
3	29/08/2019	Valve Zone 4	0%	0	9%	509	-9%
		Valve Zone 3	31%	1629	24%	1277	7%
		Valve Zone 2	54%	2859	55%	2970	-1%
		Valve Zone 1	15%	813	12%	655	3%
4	30/08/2019	Valve Zone 4	0%	0	12%	518	-12%
		Valve Zone 3	30%	1359	25%	1125	5%
		Valve Zone 2	52%	2334	48%	2151	4%
		Valve Zone 1	18%	807	16%	702	2%
5	30/08/2019	Valve Zone 4	0%	0	11%	572	-11%
		Valve Zone 3	36%	1944	24%	1296	12%
		Valve Zone 2	43%	2322	53%	2862	-10%
		Valve Zone 1	21%	1134	13%	675	9%
6	30/08/2019	Valve Zone 4	0%	0	11%	605	-11%
		Valve Zone 3	36%	1947	26%	1377	11%
		Valve Zone 2	52%	2831	50%	2689	3%
		Valve Zone 1	12%	622	14%	7229	-2%



PGR = GammaRay PSP = Spostaneous Potential PDEN = Density PNEU_SD= Neutron PPEF = Photoelectric Factor

Figure 11. Comparison between DAS results and ILT measurements, pilot injector. Source: Ecopetrol database and (Sanchez et al, 2021).

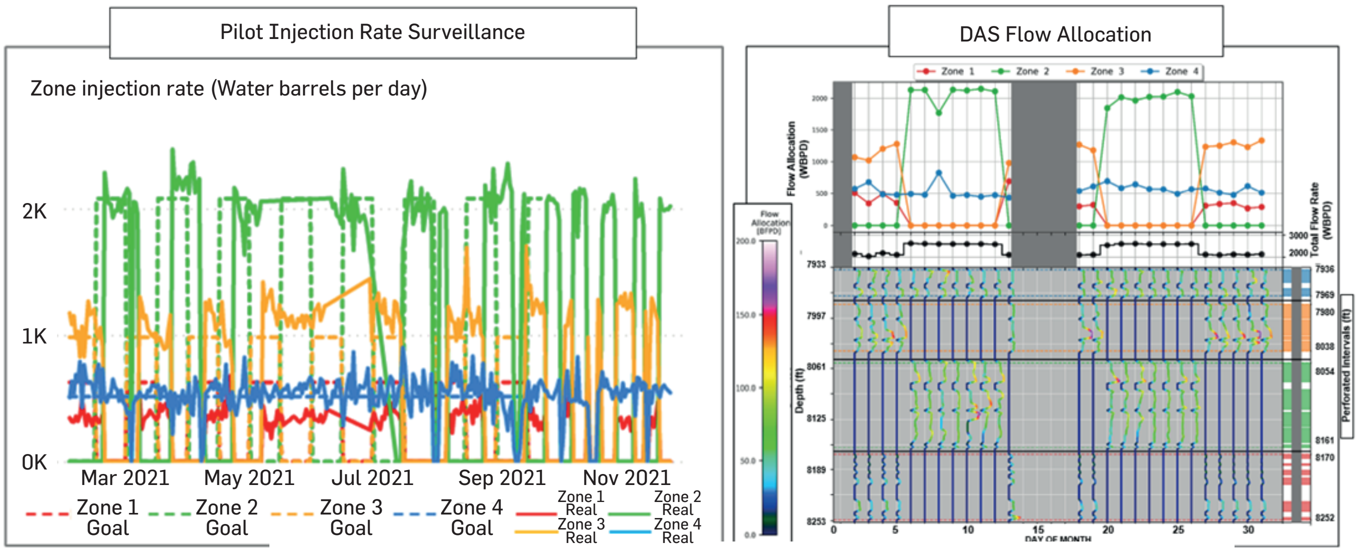


Figure 12. History of injection cycles applied on the prototype pattern (left); detail of the month-by-month injection allocation process (right). Source: Ecopetrol database.

5. RESULTS

At the time of this publication, the well has 26 cycles , each with 2 phases, for an uninterrupted 28month period. Producing wells were affected for a few hours after the start of the cycles. Notable effects on production, injection and pressure trends are to be highlighted; observations transform the understanding of the impact of these methods on the industry's needs in terms of energy transition. The background system works well and renders reliable information for better recovery planning. The whole pilot is a success.

A) PRODUCTION.

It was noted that the production tendency was positively affected; pressure variation is observed positively online with the cycles performed (enabled by ESP online sensors). The decline evolves from 3.1 to 2.1 m.n., proving a persistent answer for over 2 years of testing, see figure 13 and further continued.

Pressures on the sector's bottom line have been reduced since the mechanism allows displacement of overpressures of high K zones to balance them when lowering the total injection with stable or nearby stable extraction on producing wells. A better sweep control

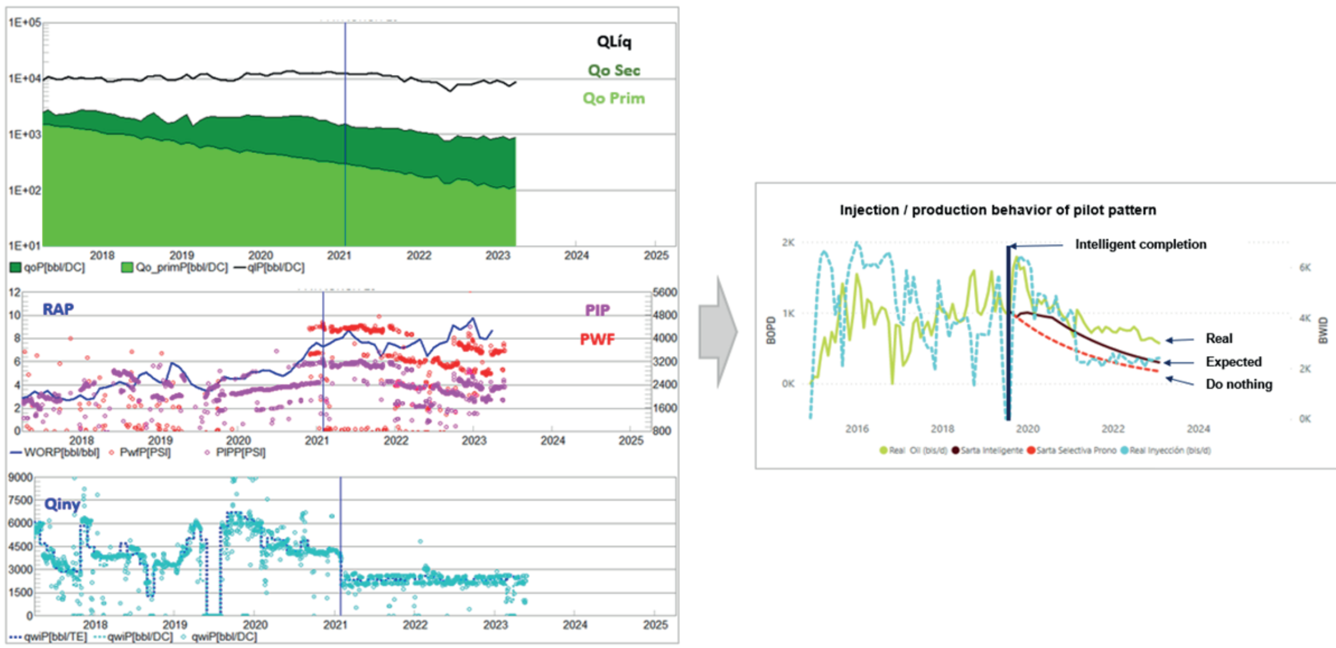


Figure 13. Detail of the production behaviour of the pattern subject to injection in cycles. Source: Ecopetrol database.

is observed. At the end, it was possible to circulate about 70% of the water at 130 psi less at the bottom than before. On the producing wells a higher delta P was reached, which positively impacts the sweep efficiency, as evidenced in production.

An energy benefit in this instance would be the decrease in system pressure in the pattern zone, which translates into lower injection pressures without overloading in liquid production. This means less energy consumption as, in fact, energy spent was reduced by about 10%.

Water injection lowered from 4500 bls/d to 2500 bls/d, 44% less water with a positive trend for production. The planned increase was surpassed, which indicates that the mechanism could be even more effective than expected from the reference simulation exercises (López & Uricochea, 2019).

B) RECOVERY FACTOR.

The observed results led to a positive alteration in the trend of the standard curve of the prototype pattern, which is like the one proposed in the authors' simulation exercises (Langdalen, 2014; López & Uricochea 2019). The process applied in a systemic manner leads to a differentiated recovery factor with additional benefits, see figure 14.

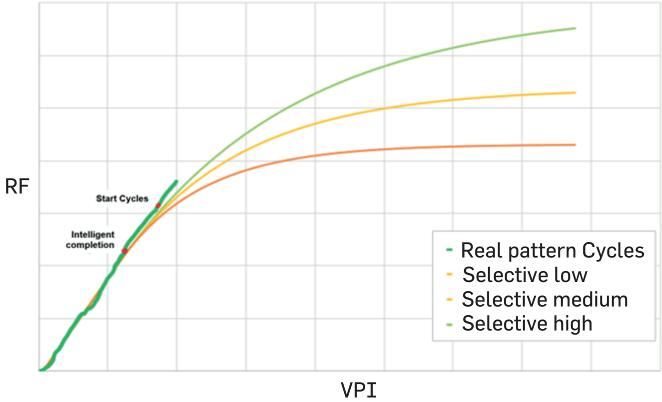


Figure 14. Detail of the trend change in the RF projection observed in the pattern subjected to the field test. Source: Ecopetrol database.

6. RESULTS ANALYSIS

A) INJECTION MANAGEMENT.

From an injection perspective, the application of cycles gave rise to a much more controlled operating philosophy, different from its preceding systems. The recovery before and after the cycles has different mystics, see figure 15.

Prior to the application of injection in cycles, 4 periods or methodologies are identified, as follows:

- Conventional injection without selective string: Inefficiency in the control of water in formation, lower injection pressures, low recovery factor in certain systems. Among them, high thickness, heavy oil crudes, and high permeability, and anisotropy are to be highlighted.
- Selective injection with conventional selective strings: It stands out for a better vertical control of water, and allows controlling the injection rate in each sub-system or zone. Nevertheless, there would be lack of control by the displacement of water through the high permeability channels at each level, among other inefficiencies. Even in this scenario, this method allows the development of the field with good performance.
- Selective injection with intelligent string (calibration period needed and definition of previous behaviour): In this period, a level of vertical control and knowledge of the injected value is achieved without precedence in the industry. The installation alone provides a difference in trends, and allows the stabilization of behaviour on producer and injector wells (more controlled flow management at each level).
- Lastly, the injection cycles with smart completion stand out for operational stabilization of the total injection, bottom pressure control, and stability in producing wells. It was clear that the most stable period was found with the latter protocol.

The times and facts that lead to understanding this evolution are:

- 2014-2015: It was the period with the conventional string, when the injection was not able to stabilize due to the inability to control the producing wells. Few feet thick water overload, loop, ILT evidence was set.

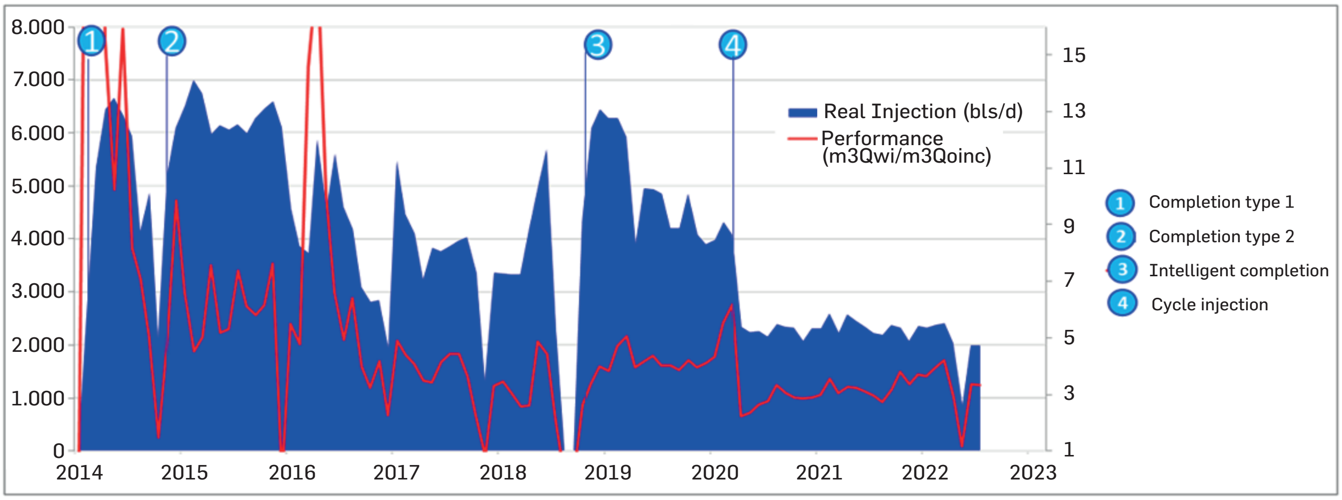


Figure 15. Detail of the change of trend in the injection behaviour in the 4 periods of the prototype injector well. Source: Ecopetrol database.

- 2015-2019: It was the period with conventional selective string, when instability results from the assurance processes to avoid channelling, periods of high and low injection, managed by high frequency team monitoring with equipment dedicated to observe the behaviour of the reservoir.
  - ◊ Operational complications stand out in valve regulation, and the hydraulics of the dedicated pump system usually turn to be incompatible with valves regulation in the same well; other problems have been water quality and crude oil viscosity. It could be said that it is the heavy crude oil itself.
  - ◊ The indication (comprehension) of how much water can be correctly injected and the fact of what made that happen using conventional valves, have a delay of several weeks: The measurement (wireline ILT), the identification of the problem (Diagnose), the adjusting (Action, wireline enabled valves change), and the new measurement that ensures that it was corrected (new wireline ILT). Even so, with operational mystique, in Chichimene this operation was successfully managed.
- 2019-March 2020: Intelligent string operation was set in a pre-cycle period. First, total injection reverse regulations were applied, which are related to the installing of new injectors in the field. Thus, typically all wells are adjusted when one or more new ones appear. After this first adjustment, which is done one layer at a time, the well showed more stability in the values planned in those periods, when producers positively respond.
- March 2020 – Present: The period with cycles operates the injection with better stability when viewed from a distant optic, totals per well, but at the bottom it's the period with the most pronounced instability in the reservoir, when opening and closing zones every 21 days. Its behaviour has been effective and has notably reduced the water consumption, improving oil rates.

B) ENERGY TRANSITION OBSERVED BENEFITS.

The combination of the operational signals of the injection process in cycles is positive; the operation with the intelligent string is successful and allows to perform the cycles, product of the understanding of the operation carried out these 2 years, with a new positive factor identified from the process: a reduction in water consumption.

During the period, less water has been injected loss-free in the crude oil production; the other way around, the crude oil trend improves, increasing efficiency in water consumption, see figure 15; nevertheless, the right amount of water saving has not been yet determined.

- In the first period of 2015, with conventional completion, the yield was 12 bls of water injected per incremental barrel.
- In the selective string period (2016-17), the water consumption was 7 IWB/STB and it was reduced to 4 IWB/STB in the period 2017-19, noticing an enhancement over time, product of the application of monitoring with surveillance teams dedicated to the injection understanding.
- In 2019, with the smart string, water consumption was extended for 1 year (it did not increase), showing that new hydrocarbon is contacted with the water and its regulation.
- In 2020, with the cycles, consumption was reduced to 3 IWB/STB, the lowest in the well's history and, after more than 7 years of total injection, new things are happening.

In this sense, injection in cycles becomes a potential decarbonizer of current and future recovery operations if the energy cycle associated with the reduction of water circulation is analysed. It should be noted that the main OPEX driver of the recovery fields is the cost of energy, and this depends linearly on water consumption and its circulation scheme.

Additionally, the worst managing of ineffective (loops) causes an immediate reduction of reserves by increasing the OPEX of the field; in some cases, it also obstructs oil production by generating overload in producing wells or surface facilities.

CONCLUSIONS

1. After a planning period, the field operator, Ecopetrol S.A., was able to implement a new type of completion for injector wells, the first of its kind in the world, which allowed a successful field test with selective injection cycles through zones that did not require operations on the surface for valve changes. The system implied daily monitoring of the well's injection profile through DAS log, also first of its kind worldwide.

2. The installed system is capable of measuring water injection with sufficient clarity and reliability, as well as being remotely operated from surface. The combined operation of a new operational technology with old techniques developed to improve water injection performance defines a new standard in this recovery mechanism, which is achieved by the evolution of the right combination of technologies and applicability developed by the operator.

3. Since the installation of the smart completion system in the well, improvements in vertical injection efficiency were evidenced, both at well and layer level, allowing to maintain injection flow rates over time and avoiding injectivity losses in the different zones.

4. The injection in cycles technique shows positive benefits in its application in the eastern plain's basin on massive sands in heavy crudes, allowing the operator to think about its application at a larger scale to increase the recovery factor of the fields under its operation and management.

5. Water injection in cycles reduces water consumption while increasing the RF, creating a condition aligned with the need to decarbonize recovery operations in the industry.

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REFERENCES

Costa, L., Rodrigues, D., da Silva, R., Souza, I., & Fernandes, M. A. (2017, October). Intelligent Completions Used during Extended Well Test of Exploratory Wells in Brazil. In Offshore Technology Conference Brasil (p. D021S014R003). OTC. https://doi.org/10.4043/28103-MS

Dyer, S., & Bouldin, B. (2016). Technology update: new intelligent completion system enables compartment-level control in multilateral wells. Journal of Petroleum Technology, 68(09), 18-21. https://doi.org/10.2118/0916-0018-JPT

Farias, M. J., & Liu, X. C. (2022, April). Optimizing Waterflooding EOR Through Cyclic Injection: A Case Study on the Hoople Field, Midland Basin, West Texas. In SPE Improved Oil Recovery Conference? (p. D011S007R001). SPE. https://doi.org/10.2118/209434-MS

Groenenboom, J., Wong, S. W., Meling, T., Zschuppe, R., & Davidson, B. (2003, October). Pulsed water injection during waterflooding. In SPE International Improved Oil Recovery Conference in Asia Pacific (pp. SPE-84856). SPE. https://doi.org/10.2118/84856-MS

Jacob, S., Bellaci, I. J., Nazarenko, P., & Joseph, P. (2015, September). Designing, planning and installation of an 8-zone all-electric intelligent completion system in an extreme reservoir contact well. In SPE Middle East Intelligent Oil and Gas Symposium (p. D021S004R001). SPE. https://doi.org/10.2118/176811-MS

Joubran, J. (2020). Application of Multizone Water Injection Downhole Flow Control Completions With Fiber-Optic Surveillance. Journal of Petroleum Technology, 72(08), 48-49. https://doi.org/10.2118/0820-0048-JPT

Langdalen, H. (2014). Cyclic Water Injection: A Simulation Study (Master's thesis, Institutt for petroleumsteknologi og anvendt geofysikk). https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/240366/736657_FULLTEXT01.pdf?sequence=2

López Rojas, A. D., & Uricochea Narvaez, N. A. (2019). Diseño de una metodología para la evaluación de la inyección de agua por pulsos para el campo Chichimene. https://repository.uamerica.edu.co/bitstream/20.500.11839/7638/1/5141839-2019-2-IP.pdf

Massaglia, E., Baldassa, D., Ponce, C., & Zalazar, B. (2006, April). Injector-Well Completion Designs for Selectively Waterflooding Up to 18 Zones in a Multilayered Reservoir: Experiences in the Cerro Dragon Field. In SPE Improved Oil Recovery Conference? (pp. SPE-99997). SPE. https://doi.org/10.2523/99997-MS

Nguyen, D., Macleod, I., Taylor, D., Murray, L., Zavyalov, D., Booth, D., ... & Shafei, S. M. (2019, September). Application of Multizone Water Injection Downhole Flow Control Completions with Fibre-Optic Surveillance in Soft Sand Reservoirs. In SPE Annual Technical Conference and Exhibition? (p. D011S014R004). SPE. https://doi.org/10.2118/196231-MS

Perez, D., Salicioni, F., & Ucan, S. (2014, May). Cyclic water injection in san Jorge Gulf basin, Argentina. In SPE Latin America and Caribbean Petroleum Engineering Conference (p. D021S014R002). SPE. https://onepetro.org/SPELACP/proceedings-abstract/13LACP/2-13LACP/D021S014R002/210339

Ross, D. (2022). Electrifying offshore oil and gas production. WorldOil, 61-65. https://www.worldoil.com/magazine/2022/february-2022/features/electrifying-offshore-oil-and-gas-production/

Sanchez, W., Coronel, I., Mora, E., Giosa, C., Satizabal, M., Leal, J., ... & Joseph, P. (2021, August). World First All-Electric Intelligent Completion System with Permanent Monitoring to Evaluate Injection Performance in a Mature Injector Well. In Offshore Technology Conference (p. D041S046R004). OTC. https://doi.org/10.4043/31323-MS

Satti, R., Bale, D., Patel, A., Nazarenko, P., Avella, O., Solorzano, P., ... & Coronel, I. (2020, October). Prediction of Zonal Flow Allocation Using Fiber-Optics Monitoring In a Complex Injector Well System. In SPE Annual Technical Conference and Exhibition? (p. D021S014R006). SPE. https://doi.org/10.2118/201632-MS

Samuel, O. B., Chandrakant, A. A., Salleh, F. A., Jamil, A., Ibrahim, Z., & Ivey, A. (2021, May). All-Electric Intelligent Completion System: Evolution of Smart Completion. In SPE/IADC Middle East Drilling Technology Conference and Exhibition (p. D011S001R003). SPE. https://doi.org/10.2118/202130-MS

Sharbatova I. N., Surguchev M. "Cyclic Influence on Heterogenous Oil Reservoirs", Nedra Publishing House, Moscow (1985) 118 (in Russian).

Shchipanov, A. A., Surguchev, L. M., & Jakobsen, S. R. (2008, October). Improved oil recovery by cyclic injection and production. In SPE Russian Petroleum Technology Conference? (pp. SPE-116873). SPE. https://doi.org/10.2118/116873-RU

Solórzano, P., Ahmedt, D., Jaimes, C., Henao, W., Vega, S., Guerrero, C., ... & Dueñas, D. (2018, June). Selectivizing a Singled Bed Reservoir, A Successfully Application to Increase the Vertical Displacement Efficiency in a Heavy Oil Waterflooding Project. In SPE Trinidad and Tobago Section Energy Resources Conference? (p. D011S004R002). SPE. https://doi.org/10.2118/191170-MS

Vidal, R., & Alvarado, R. (2014, September). Key Issues in Heavy Oil Waterflooding Projects. In SPE Latin America and Caribbean Heavy and Extra Heavy Oil Conference (p. D021S012R001). SPE. https://doi.org/10.2118/171119-MS

Wilson, A. (2018). Triple-Zone Intelligent Completions Aid Extended Well Tests of Exploratory Wells. Journal of Petroleum Technology, 70(04), 70-71. https://doi.org/10.2118/0418-0070-JPT

Yu, Y., & Sheng, J. J. (2016, May). Experimental investigation of light oil recovery from fractured shale reservoirs by cyclic water injection. In SPE Western Regional Meeting (pp. SPE-180378). SPE. https://doi.org/10.2118/180378-MS

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NOMENCLATURE

RF	*Recovery Factor.*
T2	*T2 Sand, Formation San Fernando, Llanos Basin.*
DAS	*Distributed Acoustic Sensing.*
DTS	*Distributed Temperature Sensing.*
GSJB	*Gulf San Jorge Basin.*
WF	*Waterflooding.*
Gross	*Referred to total thickness of sands.*
Shale	*Referred to ultra-low permeability rocks.*
m.n.	*Monthly nominal.*
mD	*Millidarcies.*
D	*Darcies.*
Psi	*Pounds per square inches.*
Loop	*Referred to recirculating water between well- reservoir – well systema without move any o barely oil.*
ILT	*Induction log test.*
K	*Referred to capacity of reservoir rocks to permit flow.*
OPEX	*Operating expenditures.*
IWB	*Injected water barrels.*
STB	*Stock tank barrels.*
V	*Dystra Parson Heterogeneity Coefficient. A measure of permeability difference between rocks.*
SEC	*Secondary production.*
PRIM	*Primary production.*
Liq	*Liquid*
IOT	*Internet of the things.*