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Improving the recovery factor of heavy oilfields of Marañón Basin by using new completion and EOR technologies

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ABSTRACT

Mature heavy and light oilfields in the Northern Peruvian Jungle have produced oil for more than 40 years under primary recovery mechanisms (cold production methods). According to production performance and subsurface engineering analysis, reservoirs are exploited by a strong flank, and eventually bottomhole water drive mechanisms assisted with ESPs; cumulative oil production in mature heavy oilfields has exceeded more than ***430 million barrels*** of oil with ***20%*** current average recovery factor. In addition. The ultimate recovery factor is expected to account for ***an average of 25%*** at an economic limit of approximately ***98% water cut***, by extending oil operations with conventional technology.

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This study explores the technology options to increase production and recovery of heavy oil resources at commercial rates. Technology options assessment include ***selective completion technologies and/or autonomous inflow control devices (AICDs)*** for new horizontal infill or extended wells, as well as the application of enhanced oil recovery techniques such as ***polymer injection and cycling steam stimulation (CCS),*** which also contributes with ***decarbonizing production operations*** by reducing water production with less energy consumption.

A workflow is proposed starting by modelling water encroachment mechanism by using analytical methods such as ***WOR vs. Np, Chan's curves, and Ramos' method***; this analysis is well complemented with ***numerical simulation modelling*** to determine the influence of either flank or bottomhole waterdrive (or both). Then, a ***hybrid screening process*** combining rock and fluid properties with statistics of worldwide EOR projects has been used to select the most appropriate technologies to optimize production performance and increase recovery efficiency in Peruvian heavy oilfields; ***7-parameters*** related to petrophysical properties, fluid behavior, drive mechanism and completion system were included for a ***pattern analysis*** in the screening model run by a machine learning algorithm.

Preliminary results shows that primary recovery factor in heavy oilfields would rise from **20%** (with traditional cold production technologies) **to 30%** with horizontal and multilateral drilling with new completion technologies (by using AICDs or selective production) as it is expected in ***Bretaña oilfield***, a green field whose production history started by 2018. On the other hand, enhanced oil recovery methods such as polymer flooding, cycling steam stimulation and HASD would at least double production rates and increase recovery factors by ***10% to 15%***. Lab and Numerical simulation studies, as well as pilot tests of thermal recovery methods are strongly recommended for some fields with low recovery factors such as, Bartra field in Block 192, and the Raya and Paiche fields in development stage, situated in Blocks 39 and 67 respectively.

Keywords—Heavy Oil, Recovery Factor, WOR, Cold Production, EOR Screening, Polymer Injection, CCS

I. INTRODUCTION: HEAVY OIL POTENTIAL IN PERU

The primary recovery factor of worldwide oilfields ***is estimated at 35%.*** Several countries have tested new development and operational strategies as well as new technologies to increase oil recovery in a more cost-effective manner in existing fields[1].

The relevance of the Northern Peruvian Jungle as a strategic region for the recovery of the upstream industry in Peru is considerable, due to the number of fields and oil resources (**see figure 1**), The constant decline of medium and light oil production in most of the fields in Peru in recent years along with the increase in domestic demand are indicators that all efforts should be put into the most innovative re-development strategies for the recent large heavy oil discoveries in the Marañón Basin.

According to an update of the *2022 Annual Book of Reserves and Contingent Resources of Peru* [2], more than 70% of the 3P+2C volumes are attributed to potential recoverable resources of heavy oil in the Northern Peruvian Jungle (see **table 1**). and this ratio keeps growing year after year since light oil production declines fast in the region; in particular, heavy oil blocks 67 & 39 accounts for more than ***400 MMSTB of resources*** that cannot be produced and transported efficiently and cost-effective through North Peruvian Pipeline without a diluent source or an insitu upgrading process.

[1] *Babadagli, T. (2005). Mature Field Development – A Review. SPE 93884.*
[2] *Ministry of Energy and Mines, Directorate General of Hydrocarbons (DGH), 2022 Annual Book of Reserves and Contingent Resources of Peru*

Table 1: Update of the oil reserves and resources as of 31/12/2022 report, Loreto Region, Marañón Basin

LOTE	Reservas Probadas (P1) MMSTB	Reservas Probables (P2) MMSTB	Reservas Posibles (P3) MMSTB	Recursos Contingentes (2C) MMSTB	Producción Acumulada a Dic 2023 MMSTB
8	32.3	3.8	0.0	0.0	333.1
39	21.0	60.9	41.6	52.2	0.0
64	27.5	15.5	46.7	43.8	0.0
67	26.3	48.7	137.7	15.7	4.4
95	48.0	52.2	99.4	0.0	16.7
192	126.3	0.0	0.0	82.2	737.5
TOTAL	281.4	181.1	325.4	193.9	1091.7

An increase in the recovery factor in heavy oilfields of north Peruvian jungle is strongly dependent on proper completion technology, well placement and trajectories, availability of of heavy oil diluent, economic feasibility of oil transportation, and effective reservoir management strategies[3]; many of these factors are strongly influenced by a sustainable management of field operations.

It should be noted that in many cases, the recovery factors for Vivian and Chonta formation in light oilfields are above 35% (**see figure 2**), and there is still left and by-passed oil that can be recovered, particularly in heavy oilfields. Based on that, a strong correlation between recovery factor and "a kind" ***of mobility index*** $(\frac{KoAPI}{\mu o})$ was derived with data ***from 25 mature oilfields producers*** in Marañón Basin (see **figure 3**); upper and lower limits surrounding observations were included. In addition, ***figure 4*** shows the same plot and correlation for heavy oilfields, which sustain ***that average recovery factor*** with cold production technologies ***should not be less than 25%***; as a result, Bartra, Jibaro-Jibarito and San Jacinto fields can be evaluated with further detailed engineering studies to come up with new development plans allowing increasing their oil recovery.

In addition, this analysis was extrapolated to "green" heavy oilfields (Blocks 67, 39), in which expected recovery factors are estimated in 15%; thus, ***200 MMSTB of heavy oil resources***, which means 10% of additional volumes that might be recovered with new development plans, completion technologies and if there were a sufficient diluent source or in-situ upgrading plant.

Hence, in order to promote these new studies and the application of new subsurface and surface technologies for mature and new heavy oilfields, the Peruvian Government should play an active role to incorporate some changes to the hydrocarbon regulations, including fiscal incentives and modifications in contractual agreements (royalty release policies)[4] for heavy oil; so that operators may increase investments in exploration and production, apply new technologies and deploy field optimization with cutting-edge reservoir management strategies.

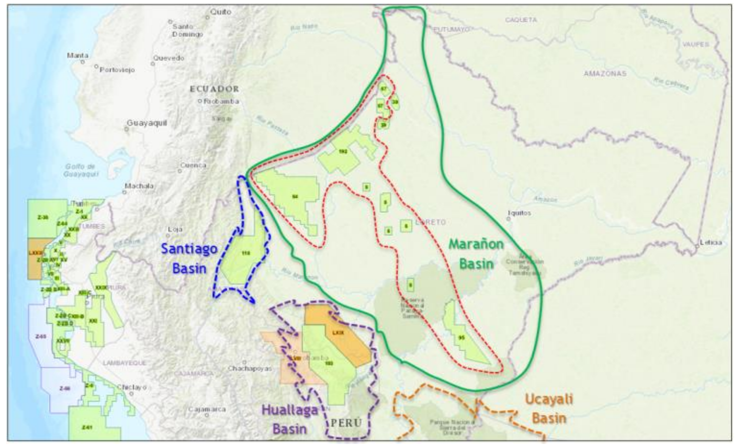

Figure 1: Marañón basin blocks 192, 64, 39, 67, 129, 123, 8 and 95 [5] have almost 1 billion barrels of oil resources.

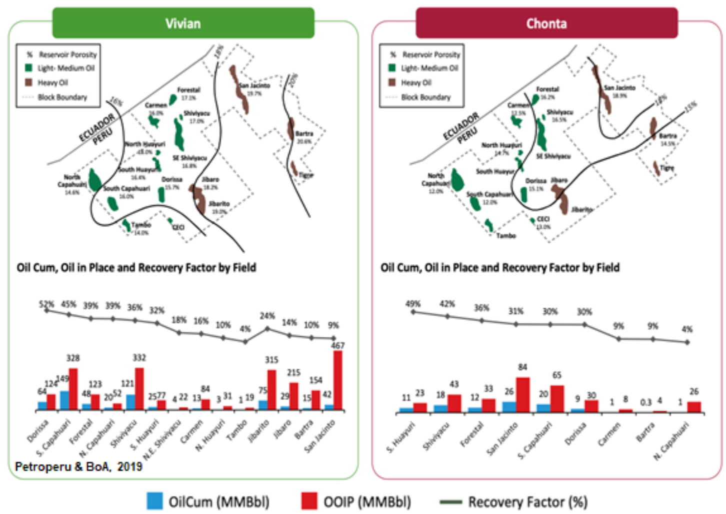

Figure 2: Current recovery factors by field in Block 192 oilfields for Vivian and Chonta reservoirs

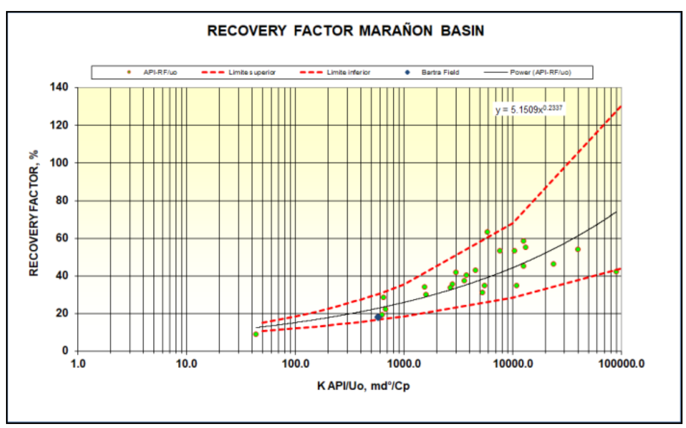

Figure 3: Expected Recovery Factor in Marañón Basin Oilfields vs. Mobility Index

[3] *Babadagli, T. (2005). Mature Field Development – A Review. SPE 93884.*
[4] *Voskanian, M. (2009). Incentives to Revitalize Mature Fields in an Environmentally Safe Manner. SPE 121819.*

[5] *Perupetro website: www.perupetro.com.pe, North Peruvian Blocks Map.*

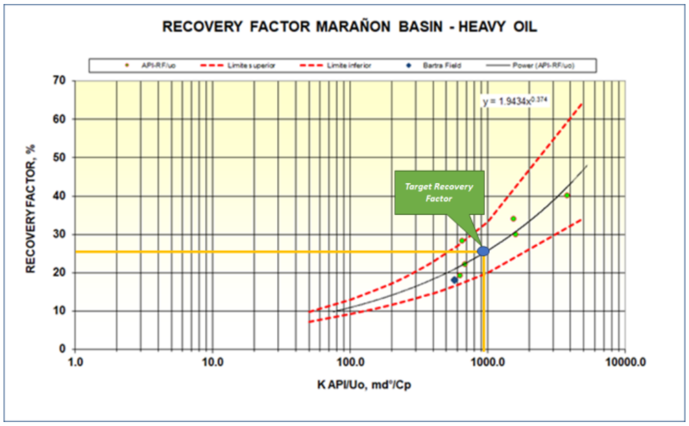

Figure 4: Expected Recovery Factor in Marañón Basin Heavy Oilfields vs. Mobility Index showing the target RF.

II. SCREENING CRITERIA FOR REDEVELOPMENT TECHNOLOGIES[6]

Worldwide case studies have shown that many strategies have revitalized mature oilfields by increasing the lifetime and primary recovery factor. These re-development strategies can be widely grouped into two major categories [7]: well engineering, such as artificial lift optimization, new completion technologies, recompletion and stimulation techniques, relocation of surface facilities and field automation; and, reservoir management, such as decreasing of well spacing by infill, horizontal and multilateral drilling; as well as secondary and tertiary recovery strategies.

The critical issue to revitalize mature heavy oilfields under strong waterdrive mechanism is to determine residual oil saturation and 'by-passed' oil zones. Thus, efforts are focused on well placement; horizontal or multilateral trajectories are recommended to increase areal and vertical sweep efficiency. In addition, well development practices such as intelligent completions with autonomous inflow control valves or devices (AICVs or AICDs) may be implemented to increase displacement efficiency and optimize artificial lift.

Screening criteria to tackle mature field re-development would involve a technology transfer process starting from ***optimization of cold production technologies*** such as horizontal wells completed selectively with AICVs or AICDs including proper ESP pumps, downhole water separation, CHOPs and waterflooding to the most sophisticated EOR applications such as thermal and chemical EOR (such as polymer flooding). ***Figure 5*** presents a ranking matrix of heavy oil technologies according to risk versus implementation difficulty. Note that the process of technology selection would start with the proper estimation of remaining hydrocarbons followed by how the expected recovery efficiency and EUR can be maximized. Additionally, the technology selection must consider optimizing fluid rates to maintain and increase production plateau as a function of facilities specs and pipelines throughputs.

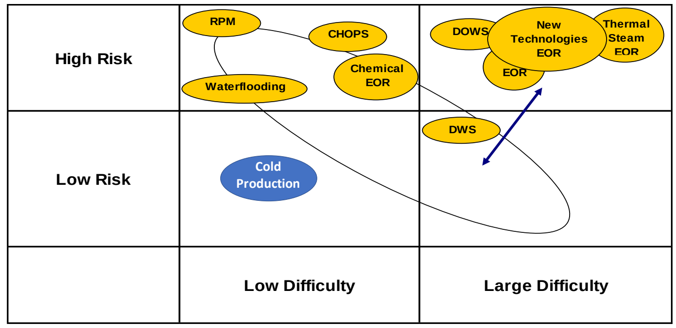

Figure 5: Technology selection matrix for heavy oilfields showing that cold production technologies with low risk and difficulty should be evaluated.

III. ANALYSIS OF PRODUCTION PERFORMANCE AND WATERDRIVE MECHANISM[8]

Most of Peruvian heavy oilfields have been discovered in the Marañón basin. Production history indicates a strong waterdrive mechanism by which oil production declines as water rate increases, whilst reservoir pressure is sustained with less than 20% of pressure decrease. For instance, production performance in the Jibarito field, a heavy oilfield in Block 192, is shown in ***figure 6***. Additionally, the pressure history of the Jibarito field shows the effectiveness of waterdrive mechanism to maintain reservoir pressure while primary oil recovery factor reaches ~**24%** (see **figure 7**).

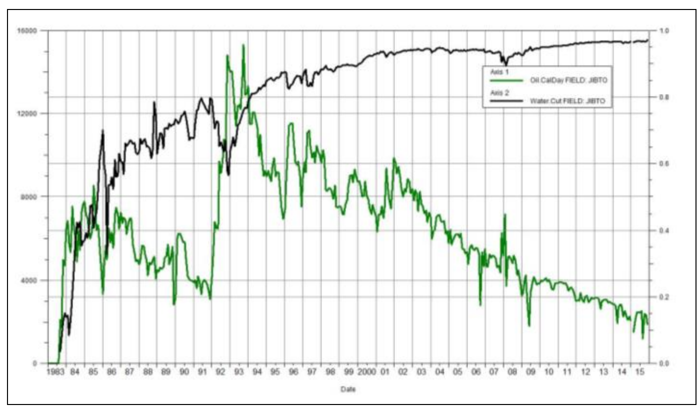

Figure 6: Production history of Jibarito field under water drive mechanism, note water cut reaching ~97%

[6] *Huerta, V. Palacios, N., Cervantes, R. (2015). Key Parameters to Revitalize Mature Oil and Gas Fields. SPE 177240.*
[7] *Babadagli, T. (2005). Mature Field Development – A Review. SPE 93884.*

[8] *Huerta, V. Palacios, N., Cervantes, R. (2016). Assessment of Cold Production Strategies to Revitalize Mature Heavy Oilfields in the Peruvian Jungle. SPE 181150.*

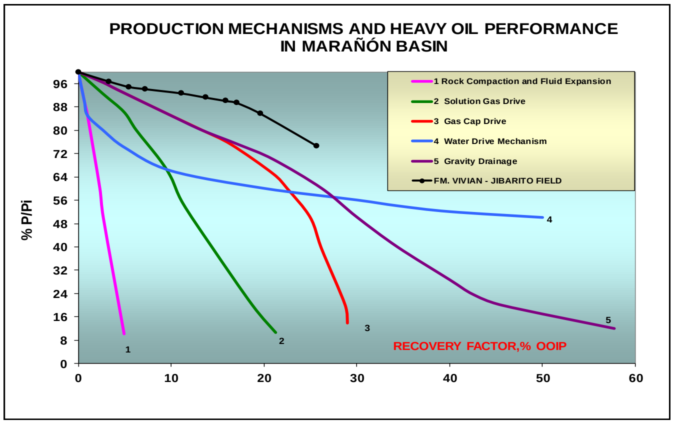

Figure 7: Drive mechanism and recovery factor for Jibarito field in the Vivian formation, note higher pressure support of aquifers in Marañón Basin.

In addition, an analysis of water movement in Yanayacu field, in Block 8 was conducted based on analytical models with production data and historical behaviour evaluation by means of a numerical simulation model. ***Figure 8*** shows Chan's curves for two of the most representative wells in Yanayacu field supporting that flank waterdrive mechanism is predominantly at the beginning of the production cycle; and eventually, bottomhole drive appears and plays a more important role in production performance.

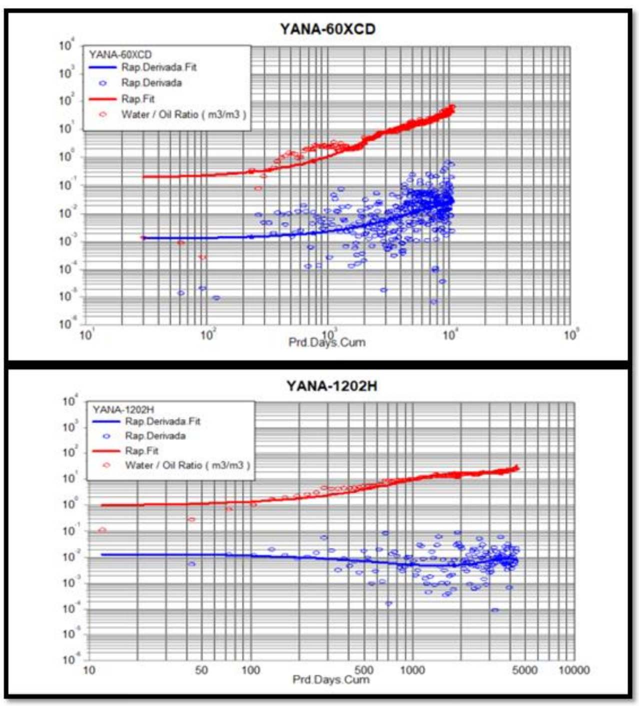

Figure 8: Predominant flank water drive mechanism in Yanayacu wells by Chan's curves

On the other hand, some dynamic structural sections were prepared for Yanayacu field from the north to the south of the structure, to assess the evolution of water encroachment during the lifetime. ***Figure 9*** shows a structural section on how the initial fluid was in Yanayacu field, and how the water moved to the wells with the predominant west flank encroachment.

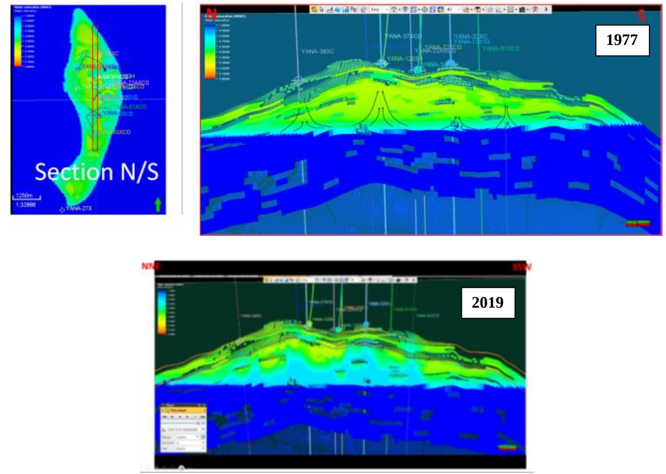

Figure 9: Structural section with initial and current fluid distribution saturation in Yanayacu field

In addition, **figure 10** shows in a N/S structural section how water saturation changed during the whole lifetime of producers in Yanayacu field; it is observed in wells 38XC, 37XCD, 32XC and 60XCD that the edge waterdrive mechanism influences the production performance first, and then once the "coning" effect is formed, the bottomhole drive mechanism makes predominant.

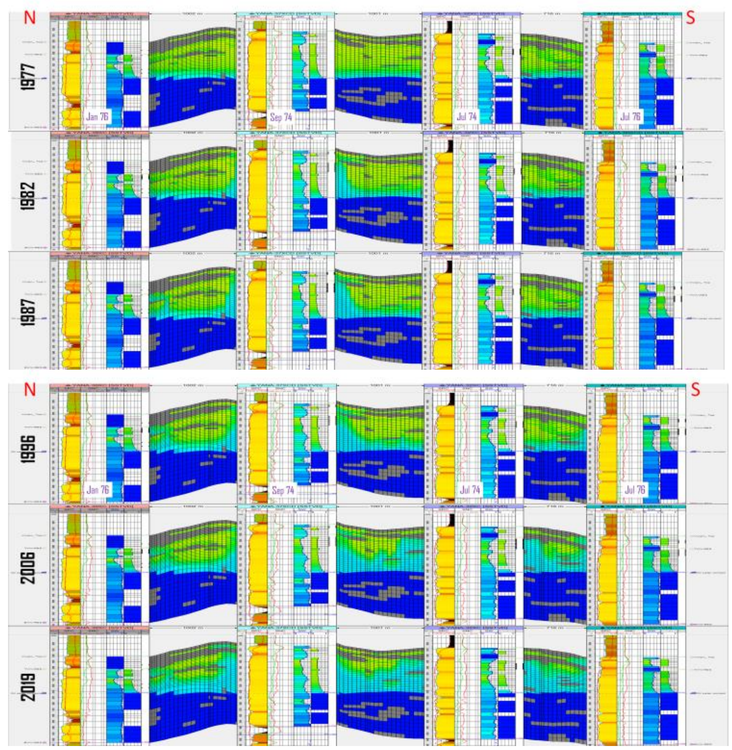

Figure 10: Predominant flank water drive mechanism in Yanayacu wells through a north – south section

Moreover, a type-curve plot between WOR and cumulative oil production was prepared for the most recent wells drilled in heavy oil fields of Block 192, 8 and 95 in Marañón Basin (**see figure 11**). It is important to highlight that Bretaña field wells are comparable to the best performing horizontal wells in Jibarito and Yanayacu fields demonstrating the effectiveness of the selective completion with AICDs/AICVs. As the WOR type curve shows a strong correlation to cumulative oil production, this curve would be used to forecast production performance of new development wells proposed for heavy oil fields in Blocks 192 and 8.

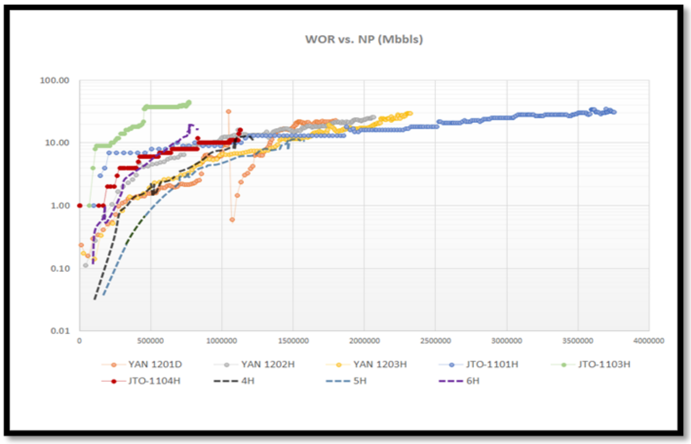

Figure 11: WOR vs. Cumulative Oil Production in Heavy Oil Fields

Figure 12 shows the correlation between WOR and cumulative oil production for heavy oil fields in Marañón Basin, as well as upper and lower bounds, characterizing the worse and better scenarios of production performance. Based on recent experiences in analogous wells of heavy oil fields in Ecuador and Peru, the upper bound may be characterizing the production performance of new development wells in Jibaro/Jibarito and Yanayacu fields completed selectively with ICDs, while the lower bound might add the benefits of a kind of polymer injection or combined chemical treatments (ASP).

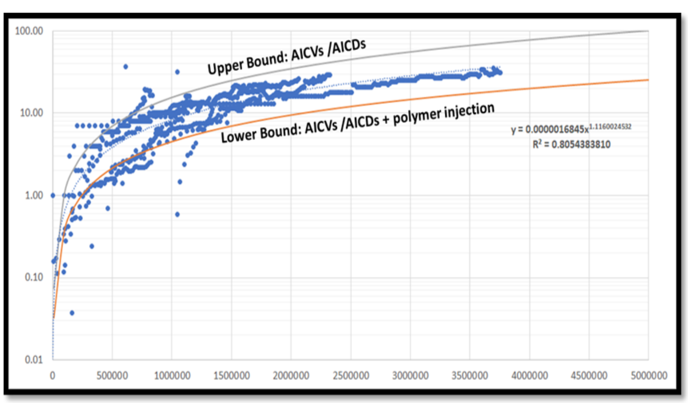

Figure 12: WOR Best Type Curve, Upper and Lower Bound vs. Cumulative Oil Production (MMSTB) in Heavy Oil Fields

IV. TECHNOLOGIES TO INCREASE OIL RECOVERY IN HEAVY OIL FIELDS [9]

Existing wells in mature fields of the Marañón basin have been drilled following slant trajectories and are only completed with slotted liners (see **figures 13 and 14**) without a selective completion. Consequently, there is no way to isolate water zones or encroachment and oil productivity and relative permeability to oil decrease rapidly as water cut increases; then, when the oil mobility ratio (M) in heavy oilfields is too low oil production is constrained and the wells are generally abandoned when water cut is too high.

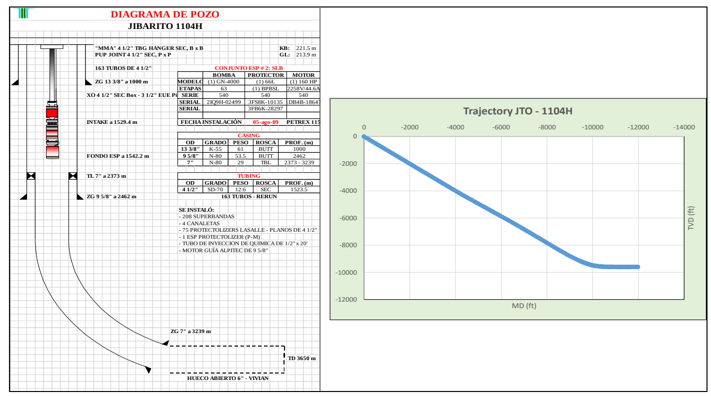

Figure 13: Well completion and trajectory of well JTO-1104H in the Jibarito field (typical well profile in Block 192)

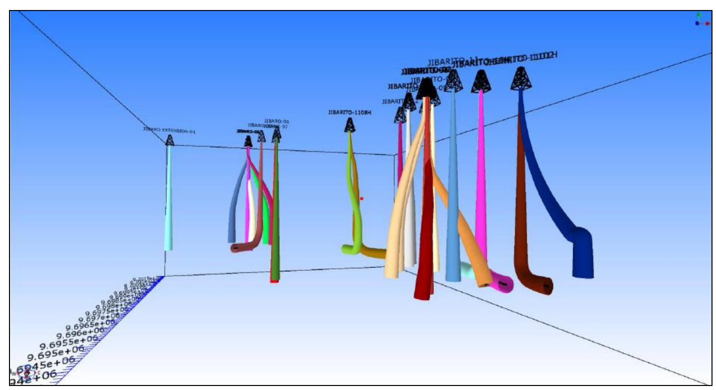

Figure 14: Slanted well trajectories in the Jibaro and Jibarito heavy oilfields, Block 192 [10]

As noted, slant well trajectories were originally used throughout the basin; however more recently, horizontal wells have been proposed for the Bretaña heavy oilfield in Block 95; which is a direct analogue of Jibaro/Jibarito fields in Block 192, with AICDs completion to delay water breakthrough while improving production performance and increasing oil recovery (see ***figure 15***).

[9] *Palacios, N. (2014). Assessment of Thermal Recovery: Steam Assisted Gravity Drainage (SAGD) to Improve Recovery Efficiency in the Heavy-Oilfields of the Peruvian Jungle. SPE 171108*

[10] *Huerta, V. Palacios, N., Cervantes, R. (2016). Assessment of Cold Production Strategies to Revitalize Mature Heavy Oilfields in the Peruvian Jungle. SPE 181150.*

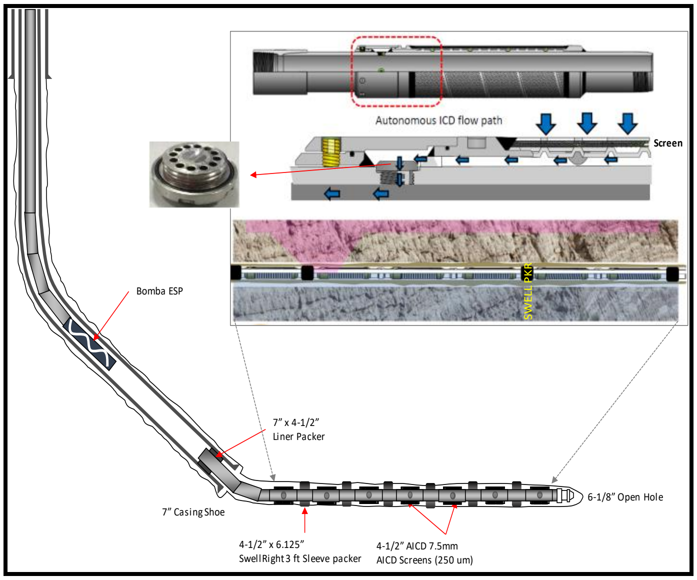

Figure 15: Well completion diagram for well BN 95-XH showing AICDs

Another alternative suggested to increase the recovery factor and prevent water breakthrough is the *Dual Completion with ESPs*. This completion type has been envisioned to be implemented in Block 192[11]; the potential upsides are listed below:

a. Better fluid distribution within the reservoir.
b. Delayed water breakthrough and minimized water cut.
c. Allows production from an isolated formation or commingled; preventing shut-in periods if one ESP fails.
d. Allows testing of each formation independently.

Before installing dual completion systems, it is recommended to run a corrosion log, verify the liner condition, and clean the wellbore. Furthermore, trajectory deviation should be between 0 and 60 degrees and dog leg severity must be less than 1. ***Figure 16*** depicts a dual completion proposed to improve recoveries in Block 192 for the main reservoirs.

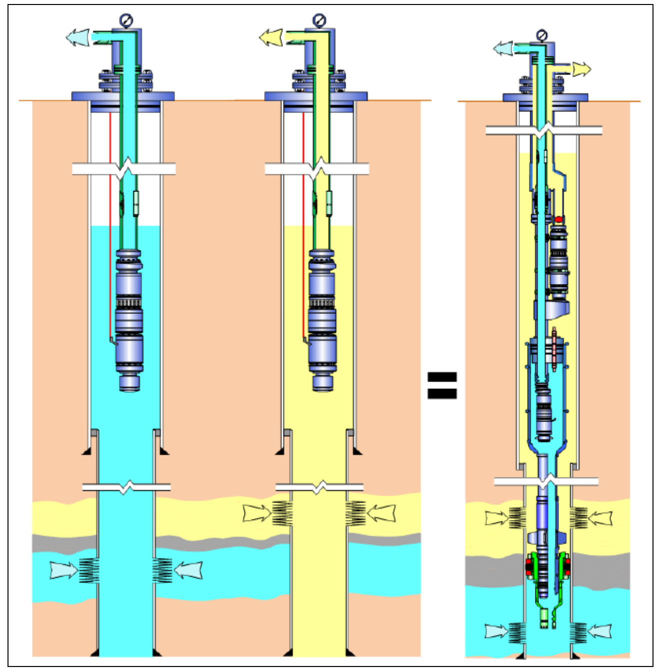
Figure 16: Dual completion diagram for a well in Block 192. Vivian and Chonta[12] formations

On the other hand, it has been proposed an EOR screening process using Machine Learning (ML) by an Artificial Neural Network (ANN). The proposed data-based detection algorithm is a high-throughput tool to select the most appropriate EOR method for a given field. This innovative approach integrates theoretical screening principles, such as the criteria developed by Taber and Al Adasani & Bai, successful EOR project practices in worldwide oilfields, a heterogeneity index criteria and synthetic data to avoid bias during screening process (see **figure 17**).

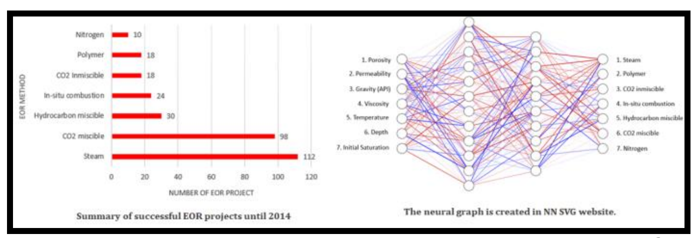

Figure 17: ANN-EOR screening model for Heavy oil fields in Block 192[13]

The analysis showed that the optimal classifier of the ANN for the EOR screening of Block 192, ***including 7 parameters*** (porosity, permeability, depth, API°, oil viscosity, temperature, and initial oil saturation), indicated that ***polymer injection and in-situ combustion are the most suitable techniques to increase the recovery factor in heavy oilfields*** with at least 95% accuracy. Implementation of these

[11] *Determination of Hydrocarbon Potential of Block 192 Report, Volume 1, Schlumberger. Sourced and authorized by Perupetro, 2019*

[12] *Determination of Hydrocarbon Potential of Block 192 Report, Volume 1, Schlumberger. Sourced and authorized by Perupetro, 2019*
[13] *Huerta, V. Meza, K. (2022) FOURTH EAGE/HGS. Application of Machine Learning for EOR Screening in Heavy Oilfields in Perú.*

techniques would require deeper subsurface engineering studies, as well as a feasibility study towards implementing a pilot project in the study area.

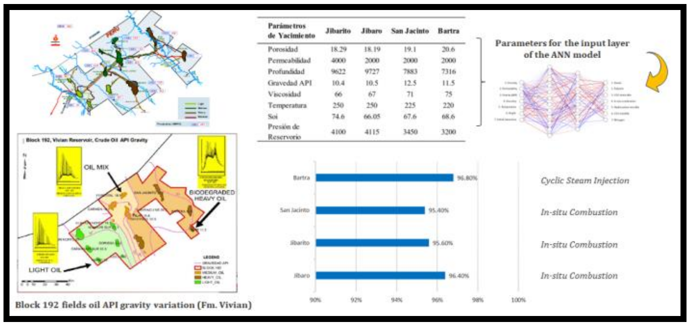

Figure 18: Application of ANN-EOR screening model for heavy oil fields in Marañón basin.

V. SUCCESSFUL CASE STUDIES APLICATIONS IN MARAÑÓN BASIN

V.1 Increased Oil and Reduced Water Production Using Cyclonic AICDs[14]

This paper explains the successful application of cyclonic autonomous inflow control devices (AICDs) for water management and the use of chemical tracers for monitoring and controlling the productivity of the different units of Vivian formation to increase oil recovery in Peru's Bretaña Norte Field by restricting the reservoir units producing mostly water. Vivian formation is an unconsolidated sandstone with an active aquifer and contains heavy oil with 20-cp viscosity at bottomhole conditions.

The field's location. Bretaña Norte Field is in Block 95 on the southeastern flank of the Marañón Basin in Peru, is in a remote and environmentally sensitive location within the buffer zone of Pacaya Samiria, natural reserve in the Peruvian Amazon; thus, there are environmental and operational challenges pushing the development plan to look for the latest technology in well drilling, completion, and production to achieve production goals while minimizing the environmental impacts. The field was put into production in June 2018 and has been developed in stages. **Figure 19** provides a map of the onshore field.

Figure 19: Bretaña Field Location (Block 95) in Peru

AICDs were identified as a technological solution to improve oil recovery. Unique chemical tracers were embedded in the sand screens to measure the oil and water production from each compartment without the need for well intervention. An integrated approach and technology workflow were used for a candidate well and included well placement using logging while drilling, predesign of AICD completions using advanced well modelling, tracer installation in the standard sand screen, and post-installation analysis of tracer samples to determine the flow contributions from each compartment and AICD performance along the wellbore. Following 1 year of production and monitoring, ***oil recovery increased by 100%*** for this well compared to that of offset wells (from 15 to approximately 30%). ***Water production decreased by almost 2 million bbl*** per year, which represents a 50% decrease in the energy required to produce and treat water (see **figure 20**).

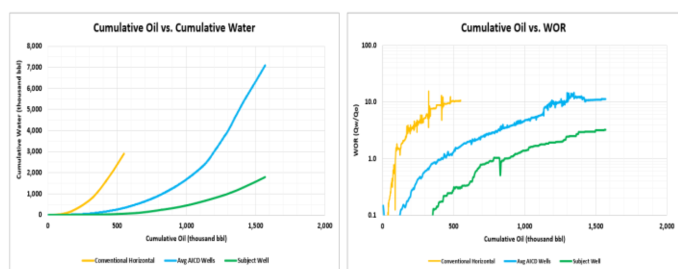

Figure 20: Comparative results: a) Cumulative water vs. cumulative oil; b) WOR vs. cumulative oil for Bretaña field wells.

Finally, these results have been extended to evaluate the use of a completion string with AICDs for a proposed drilling campaign of 3 horizontal wells in Yanayacu field of Block 8; results in this mature heavy oilfield showed a decrease in cumulative water production by **10 MMbls** of water (**10%** less than conventional horizontal completions).

[14] *L. Acencios, W. Garcia, L. Huaranga, X. Guerrero, S. Camelo, S. Gurses and B. Williams. (2023). Increased Oil and Reduced Water Production Using Cyclonic AICDs with Tracer Monitoring Applications in Peru's Bretaña Norte Field. SPE 215061*

The estimated power consumption to inject these **10 MMBBls** of water is about **35 GWh**, which means a supply of **22,000 bbl of oil for power generation**; thus, resulting in overall emissions savings about **9,300 tons of CO_2**.

VI. EXPECTED RESULTS AND CONCLUSIONS

a. There is important hydrocarbon potential in Marañón Basin blocks with significant recoverable volumes of heavy oil (***70 % of 3P + 2C resources of Marañón Basin***).
b. Cold production reservoir management strategies to revitalize mature heavy oilfields in Peru would include horizontal drilling with selective completion or completion with AICDs to increase oil recovery and delay water breakthrough; preliminary estimations indicates that effect of selective completion with AICDs/AICVs ***may rise recovery factor in mature heavy oilfields from 20% to 30%***.
c. The successful application of cyclonic AICDs with chemical tracers for monitoring in Bretaña Norte Field demonstrates that the oil production and recovery factor of heavy-oil fields with a strong waterdrive can be improved. This case study, which provides the results of 1 year of production, can serve as guidance for similar fields throughout Latin America.
d. Preliminary results showed that application of AICDs in mature heavy oilfields would reduce total water production by 10%; this means that ***each million barrel of water production reduction***, will save 3**.5GWh of energy and 0.93 tons of CO_2**
e. The ***ANN EOR screening method with 7 classifiers*** proved to be effective in selecting polymer injection and in-situ combustion are the most suitable techniques to increase the recovery factor in heavy oilfields with further detailed studies.

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