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Monitoring and Optimization of an In-Situ Combustion Pilot Applying STAR™ Technology

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Abstract

An in-situ combustion (ISC) pilot project was operated in the Quifa heavy oil reservoir in Colombia from Nov 2011 to July 2014. A modified inverted-nine spot pattern was used. As part of the project all wells were instrumented with pressure and temperature devices.

Parameters such as bottom hole temperature and pressure, gas composition (N2, CO2, CO, O2, SO4, H2S and hydrocarbons), water composition (minerals, pH), oil gravity and gas, oil and water production rates were measured and analyzed daily in order to control the combustion process resulting in improving the volumetric sweep efficiency and oil recovery factor. The continuing monitoring of these variables helped redirecting the combustion front, optimizing air injection and increasing production.

This paper introduces the STAR™ (Synchronized Thermal Additional Recovery) technology, based on ISC concepts, which aim increase the recovery factor and creating value in ISC in a heavy oil reservoir. STAR™ is based on the Synchronization Integrated Model (SIM), a suite of software applications which help to generate the main combustion-related parameters such as H/C ratio, oxygen utilization, air-oil ratio (AOR), air requirement, etc.; evaluate the process performance and identify the position of the combustion and fluids fronts in real time.

Introduction

Quifa oilfield is located in the Eastern Llanos basin in Colombia. It has been described (Dasilva et al., 2013) as a monocline structure dipping up to the southeast, slightly deformed by synthetic or antithetic normal faults of small displacement. The main producing formation is called Carbonera Basal, known as "Arenas Basales", a succession of sandstones and shales, with fine to coarse grains and porosity between 25 and 33%, permeability in the order of 5-10 Darcies and net-pay thickness from 7-50 feet. Oil gravity ranges from 13 to 14° API, gas-oil ratio is 7 SCF/bbl, and oil viscosity ranges from 180 to 300 cp at reservoir conditions. Figure 1 shows the geographical location of the field.

One of the main characteristics of the reservoir is the presence of a strong bottom aquifer, responsible for the high water cuts observed in most wells. Recovery factors in Quifa under primary production have been estimated to be 12% for vertical wells and 22.3% for horizontal wells.

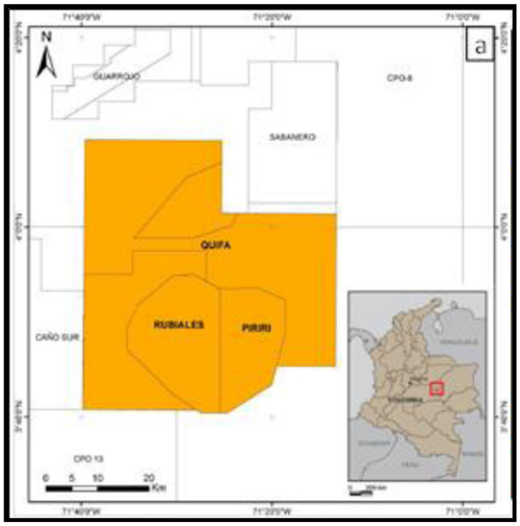


Figure 1—Location of Quifa Field in the Eastern Llanos Basin.

An EOR screening study was carried out for the Quifa field, which showed that in situ combustion (ISC) is the best process to be applied in the field, especially because of conditions favoring ISC, such as bottom water drive, shallow depth (3,000 ft), relatively low formation thickness, high permeability and high mobility ratio (>100). By applying heat, the oil viscosity is greatly reduced, together with the mobility ratio, making thermal recovery through in-situ combustion the ideal EOR method for developing this heavy oil asset, with a strong aquifer. STAR™, developed for this purpose, was found to be the best technique to be implemented after considering others such as THAI, COFCAW, COSH, and Top-Down ISC.

In this paper, we describe the monitoring plan that was designed to collect and analyze the necessary data to effectively control the process by implementing the STAR™ technology, which is supported by the Synchronization Integrated Model (SIM), a group of several software applications called sub-models that help to estimate the most important combustion-related indicators, influence the movement of the combustion and fluids fronts and hence maximize the ultimate recovery.

In-Situ Combustion

ISC is one of the thermal EOR methods available for heavy oils, and is preferred over other methods such as steam injection in special cases such as deep formations (high injection pressure required, heat losses from the injection well), limited fresh water supply, presence of an aquifer, clay swelling with injected water, and thin or low-porosity sands.

As contrasted with steam injection, during ISC the heat is created in the reservoir when the oxygen in the injected air reacts with a fraction of the crude, creating a combustion front that moves through the reservoir as the air is continuously injected. The fuel utilized during this process is commonly referred as 'coke', and is created as a result of cracking reactions occurring ahead of the main reaction zone, at temperatures above 500°F. The oil burned represents about 10% of the oil in place. ISC can be seen as a *combination* EOR process as it includes steam, water, CO2 and gas displacement all together, as well as improved oil mobility due to the reduction of the oil viscosity with the heat generated during the process.

Like any other displacement process, it is imperative to achieve high volumetric sweep efficiency, i.e., a homogeneous, symmetrical combustion front displacement, in order to improve the oil recovery and hence the project economics. The aim of the STAR™ technology is to develop the tools to control de combustion front and achieve such high volumetric efficiency.

Description of the Pilot

The main objective for the implementation of the ISC pilot in Quifa field was to develop and apply the Synchronization Integrated Model (SIM) to monitor and manage the project, which is the key element of the STAR™ technology. Other objectives were:

1. Evaluate the applicability of ISC in Quifa heavy oil field.
2. Assess the impact of the reservoir heterogeneities on the process performance.
3. Gain experience and accuracy on the simulation and analytical models developed during the pilot operation.
4. Identify possible operational problems that may arise during the project, such as emulsions, sand production, corrosion and gas blocking of ESP pumps, and identify the best solution for them.

The layout of the pilot is displayed in Figure 2. The pattern consists of 4 vertical, inner synchronizer wells (SI-1, SI-2, SI-3, and SI-4) and 4 deviated, outer synchronizer wells (SE-1, SE-2, SE-3, SE-4) with the air injection well located close to the center, resembling an inverted nine-spot pattern. The areas for the internal and external well arrangements were 5 and 15 acres, respectively.

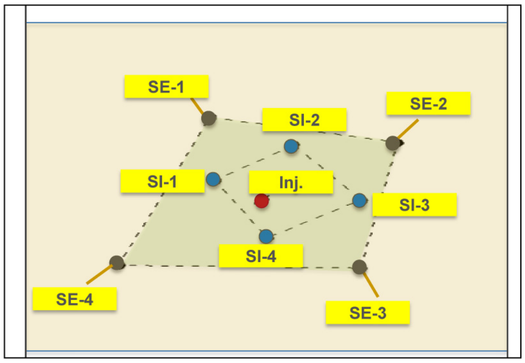


Figure 2—Well arrangement in pilot project area.

The initial injection well was produced for 2 months in order to reduce oil saturation around it. It was replaced by another injector in late 2012 in view of mechanical failure. Since there is no free gas in the formation, it was decided to create an initial gas saturation that would facilitate air injection. A total of 16.78 MMSCF of nitrogen were injected into the formation in 4 separate batches. Also, steam was injected prior to the air as the ignition technique for the pilot.

Air injection was initiated in February 2013 with 1.7 MMSCFD, and gradually increased to 4.5 MMSCFD in May 2013. The rate was later reduced to 3.0 MMSCFD in June 2013, after reaching stable burning conditions and to avoid gas migration out of the pattern due to the temporary closure of some production wells (Figure 3).

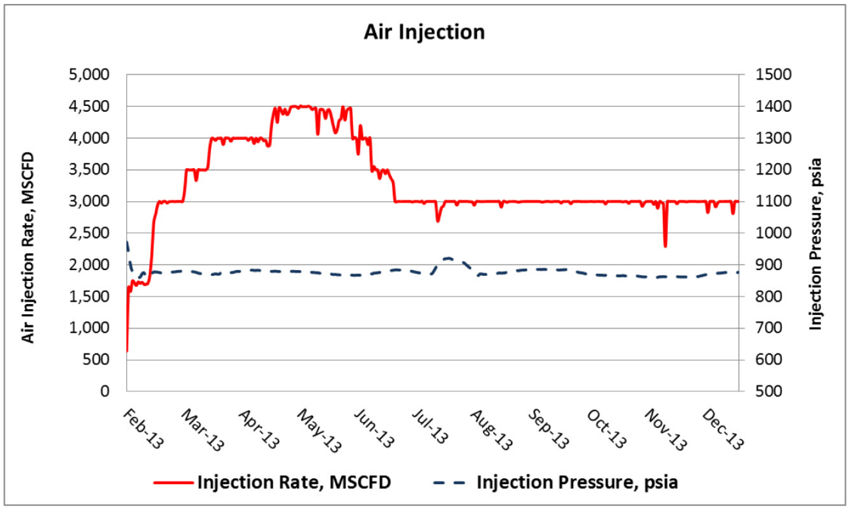


Figure 3—Air injection performance.

Process Monitoring

In order to control and achieve a high efficiency with the ISC process, there must be a real-time monitoring of the main operating parameters of the project, so as to show the progress of the combustion front, which is dependent on the injection and production well conditions (pressure and rate) and formation heterogeneity, among others. The way the combustion front moves, both areally and vertically, would determine the volumetric sweep efficiency, which in turn will maximize oil recovery.

A monitoring plan was implemented with the following objectives:

1. Define and measure the main variables that govern the process.
2. Specify the source and frequency for measuring and reporting the data.
3. Define how to analyze, process, integrate and visualize the collected variables.
4. Support the Synchronization Integrated Model, which allows timely decisions to uniform the geometry of the combustion front.

The flow chart displayed in Figure 4 summarizes the monitoring process designed and implemented, from data gathering to the final definition of synchronization activities to improve the performance of the pilot.

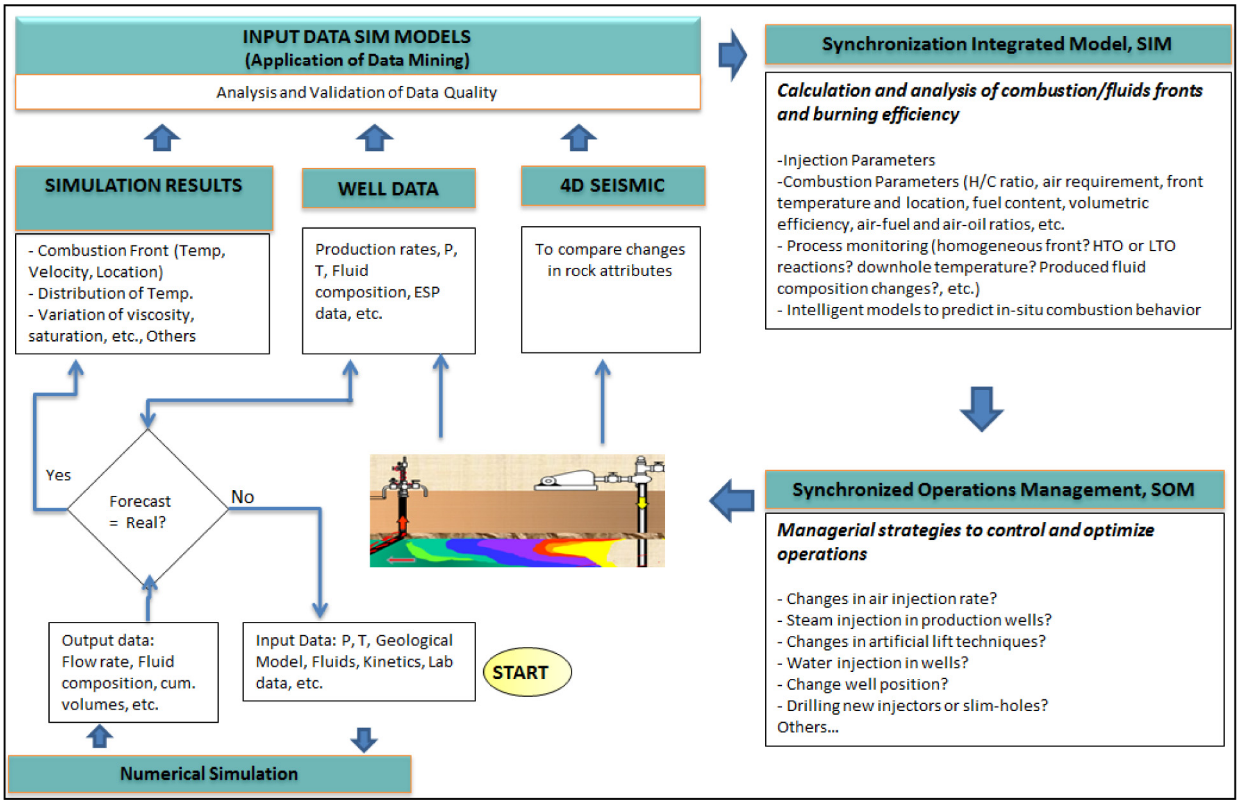


Figure 4—STAR Project Monitoring and Control.

All producing, synchronizer wells were equipped with bottomhole pressure gauges (bubble tubes), thermocouples and optical fibers for temperature readings, as well as pressure and temperature sensors at wellhead and ESP pump intake. A web portal was designed to have all these data available remotely in real time. One of the viewing panels is depicted in Figure 5.

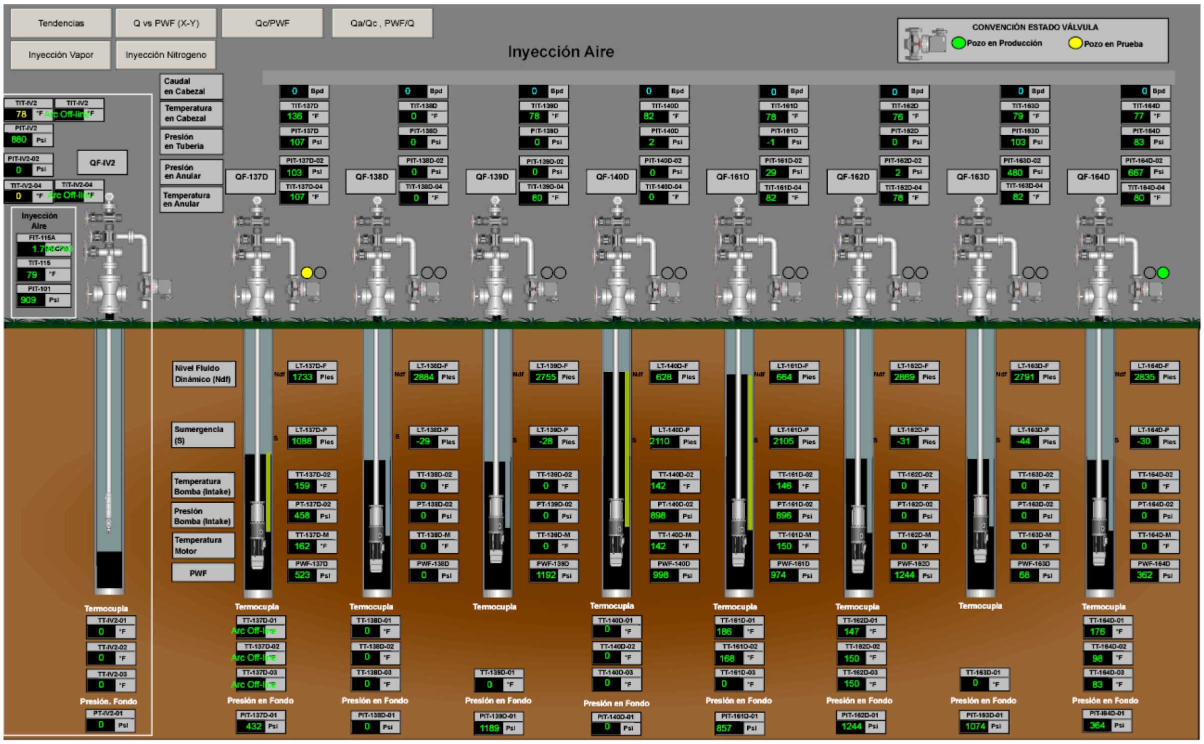


Figure 5—Visualization of surface and sub-surface well parameters.

Fluid data collected before air injection

Fluid analysis is a key element in monitoring the advance of the combustion front and the type of reactions that take place.

The gas analysis helps to confirm that ignition has occurred, monitor the combustion efficiency, estimate the progress of the combustion front and displaced fluids and ensure that the process is being conducted in the HTO mode and safely (low O2 and H2S content). Also, the water analysis carried out in each well provides information about the proximity of the combustion front, as well as the chemical oxidation processes that are carried out in the formation (LTO vs. HTO).

During the *cold* production period, before air injection, several fluid parameters were measured in order to have a base line to compare against, once the fluids were affected by the combustion reactions. The main parameters were:

- Water: pH, alkalinity, conductivity, ions (Ca, Na, Cl, Mg), sulfates, dissolved solids.
- Gas composition: O2, CO2, CO, N2, H2S, CH4 and other hydrocarbons.
- Oil properties: API gravity, viscosity, acid number, asphaltene content.

Besides the above data, three combustion tube tests were performed under different control conditions, with the purpose of evaluating the combustion characteristics of the Quifa crude oil and the major combustion-related parameters such as fuel content, air requirement, gas composition, air-fuel ratio, and others. Finally, a detailed geological model was built using the available 3D seismic, well logs and core analysis available from one the pilot wells.

Fluid and operating parameters measured during ISC

Monitoring of the combustion processes was achieved by the analysis of the produced-fluid composition, as well as by temperature, pressure and flow rate measurements. A list of the main parameters collected and their source are presented below.

Main operating parameters:

- Injection well: air injection rate and pressure, and air composition.
- Synchronizer (producing) wells: Oil, gas and water rates; wellhead and bottomhole pressure and temperatures; ESP intake pressure and temperature.
- Facilities: flow rates and gas composition at separators and H2S process plant.
- Reservoir: 4D seismic.

Fluid parameters:

- Oil: API, viscosity.
- Gas composition: molar fractions of O2, N2, CO2, CO, CH4, C2H6, C3H6 and H2S (ppm), at wellhead, separators and the H2S process plant.
- Water: pH, alkalinity, conductivity, ions (Ca, Na, Cl, Mg), sulfates, dissolved solids.

Figure 6 shows the O2 and CO2 concentration (normalized) for the main gas stream coming from all wells, measured at the H2S plant. As can be noted, there were only 3 instances where O2 content reached values higher than 3.0%. The CO2 content was generally higher than 14% for the period considered, indicating good combustion characteristics of the process.

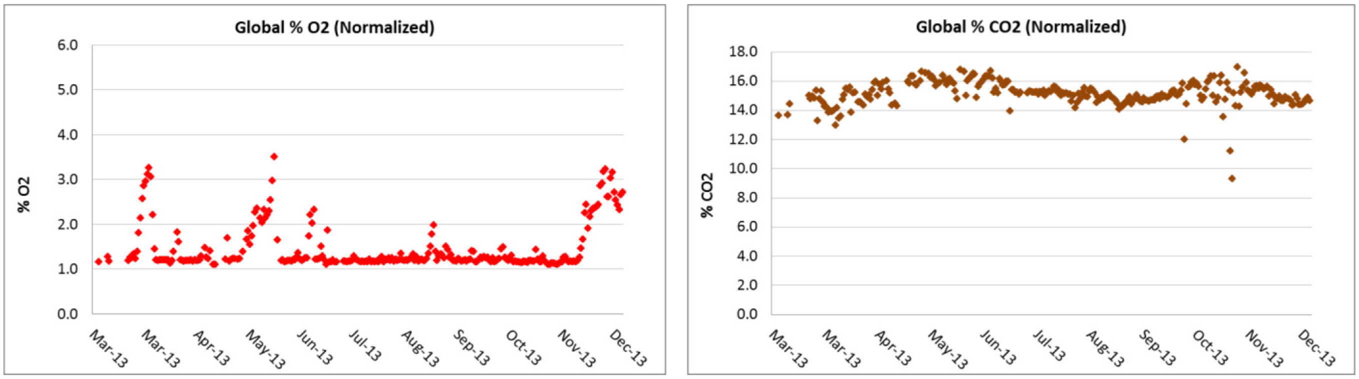


Figure 6—Average mole concentration of O2 and CO2 in total produced gas

Table 1 presents the average gas composition for the field, for the period Feb-Dec. 2013, compared with the composition range obtained in the three combustion tests performed for Quifa. The close agreement seen in both cases also indicates the good combustion performance achieved in the pilot, as the gas composition from the lab tests are usually obtained with high temperature reactions, in a highly efficient process.

Table 1—Average gas composition in the project vs. composition range in lab tests

Component	Average Content (field), % mol	Content in lab tests, % mol
O2	1.6	0.1 - 1.4
N2	82.6	80.9 - 82.4
CO	1.2	3.4 - 4.2
CO2	14.7	13.3 - 14.6

As for the water analysis, Figure 7 and 8 show the pH of the produced water from all wells. The average value for Quifa is around 8.0, and as it can be seen, pH was as low as 3.0 for two of the internal wells, and 4.0 for two external wells. The decrease in the water pH is one of the changes observed in the produced water coming from those wells affected by combustion reactions. Another parameter that is affected is the sulfate content, and as it is shown in Figure 9, sulfate concentration increased as the pH decreased, a behavior that also helps identify the movement of the combustion front towards a particular well.

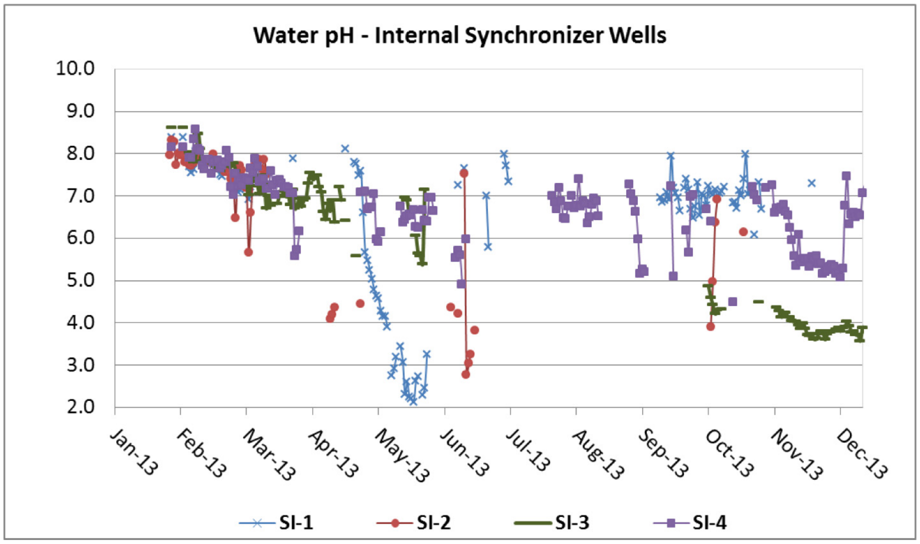


Figure 7—Produced-water pH for internal synchronizer wells

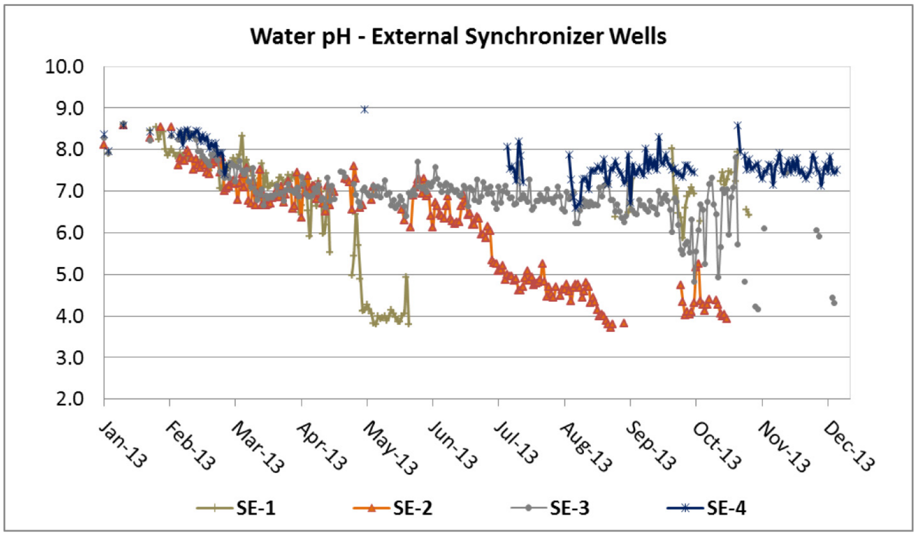


Figure 8—Produced-water pH for external synchronizer wells

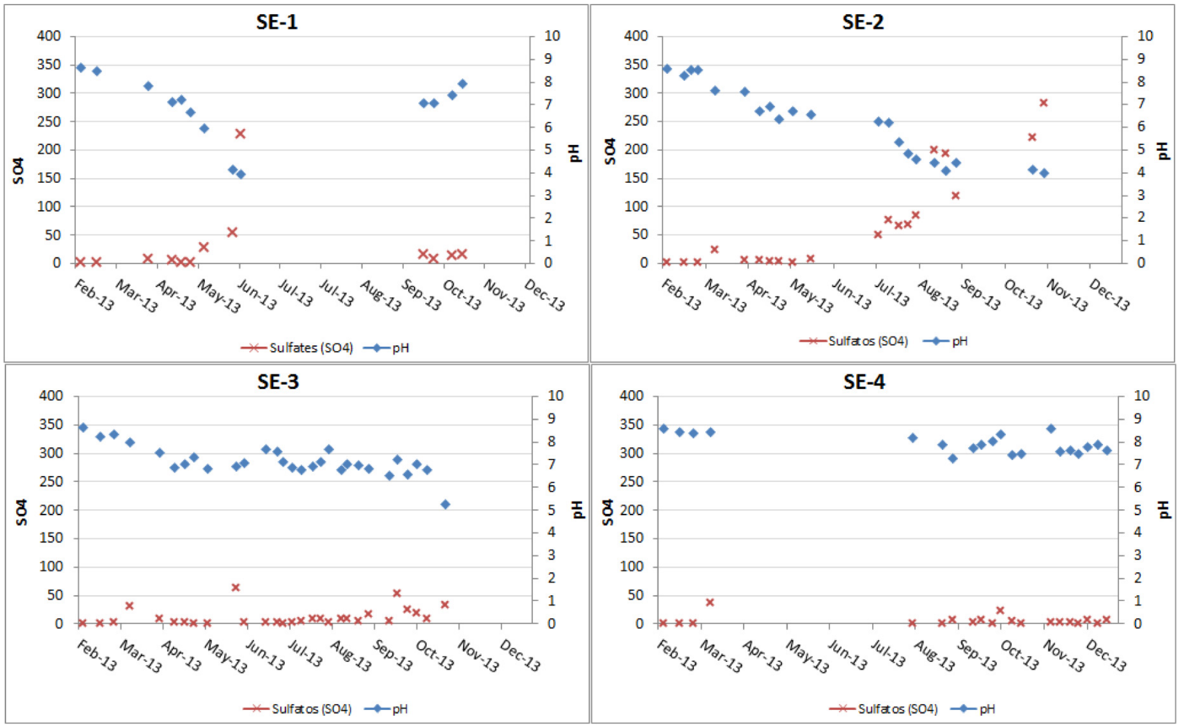


Figure 9—Produced-water Sulfate concentration and pH. External Synchronizer wells.

STAR™ Technology

The STAR™ technology was developed by Pacific Rubiales Energy to increase the recovery factor and create value in most of the heavy oil crudes reservoirs. The Synchronization Integrated Model (SIM) is the main support of the STAR™ technology. It is an innovative system developed to identify and control the combustion and fluid fronts, monitor the development of the ISC process in real time, and synchronize well operations to positively affect the combustion process.

The SIM comprises a series of modeling tools that facilitate timely decision-making, aiming to increasing volumetric sweep efficiency and hence the reserves. It is built with data from 3 major sources: numerical simulation, wells and facilities (production and fluids data) and 4D seismic (Figure 10).

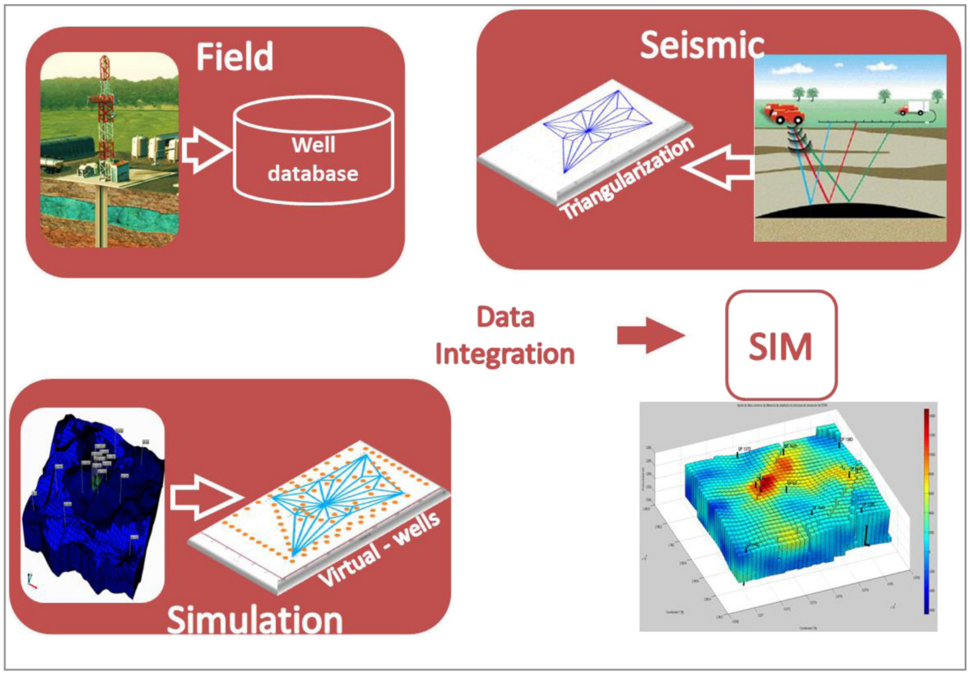


Figure 10—SIM data integration process

The well data group integrates data gathered in the wells such as flow rates and composition, pressure, temperature, as well as laboratory analyses. The bulk of the real time information comes from an operational database created for that purpose. Another group of data comes from the production facilities, including lab analysis.

The simulation data group consists of both the numerical reservoir simulation and the well production simulation (nodal analysis). Finally, the 4D seismic data group gives timely information on changes of seismic attributes, such as elastic rock properties, P and S wave velocities and amplitude, influenced by the combustion process.

The SIM applies mathematical techniques, artificial intelligence (A.I.), probabilistic reasoning, and mechanisms of statistic interpolation and inference like Kriging to manage the data and generate the four major applications called sub-models (SM), which allow for the synchronization and control of the operations. These four major SM are called Analytical, Surface-Subsurface Integrated System, Intelligent Surveillance and Control of Combustion and Fluids Fronts and Prediction of ISC Project Behavior.

The *Analytical* SM is based on several correlations widely known and used in the industry to estimate the main combustion and production related parameters (Nodwell, J. et al, Fassihi, et. al). For this purpose, the minimum data required are:

- Air injection rate.
- Oil, water and gas production rates.
- Gas-produced composition, mainly CO2, CO, O2 and N2, on a dry basis.
- Reservoir-related: porosity, fluid saturation, temperature, static pressure, average thickness, pattern area.
- Combustion-tube tests: fuel content, air requirement, core porosity.

The *Surface-subsurface integrated system* SM is used to supervise and manage production under the effects of combustion. Each synchronizer well is modeled with a multi-phase flow simulator (nodal analysis) to generate multiple production scenarios that might occur during the ISC process, such as sand production, low efficiency of ESP pumps, changes in the gas-liquid ratio (GLR) and water cut, changes in productivity index and temperature, etc.

The *Intelligent Surveillance and Control of Combustion and Fluids Fronts* SM is used to estimate the current position of the combustion and fluid fronts with respect to all synchronizer wells, as well as provide information about the combustion front velocity, rock volume burned, oil displaced, oil burned and others.

Finally, the *Prediction of ISC Project Behavior* SM helps to identify the front trajectories towards each synchronizer well under current operating conditions, and later will predict the movement of these fronts under different operational strategies.

Some of the strategies selected to train the SM for combustion front trajectory include closing synchronizer wells, changes in ESP frequency, changes in air injection rate, and steam injection in synchronizer wells.

In this paper we will show the main results obtained with the *Analytical* and the *Intelligent Surveillance and Control of Combustion and Fluids Fronts* Sub-models.

Main computed parameters

The total set of combustion-related parameters computed during the course of the project with the SIM can be divided in three main categories: operating, combustion and reservoir parameters.

The main *operating* parameters computed were the N2 factor, defined as the fraction of N2 produced vs N2 injected; combustion front velocities in the direction of each synchronizer well, oil displaced from burned and unburned zones and air-oil ratio, AOR. The N2 factor is an important variable to understand how and where the gas flows in the formation, which is also an indication of where the combustion front is moving.

The *combustion* parameters computed and analyzed included the apparent atomic H/C ratio, oxygen utilization, percentage of oxygen converted to carbon oxides, air requirement, and air-fuel ratio. These data become important to evaluate how stable and efficient the combustion is developing in the formation, in terms of the type of reactions occurring (LTO vs. HTO write in full) and how the process deviates from the results observed with the combustion tests in the laboratory, which are carried out under controlled conditions to operate in HTO mode and achieve high sweep efficiency. These combustion parameters are calculated based on the produced gas composition, air injection rate and with data obtained from the lab tests, such as the fuel content.

The *reservoir* parameters included in the study were basically the rock volume burned, combustion front geometry and location, rock volume affected by steam, volumetric sweep efficiency, oil recovery efficiency from unburned zone and the total oil recovery factor. These parameters basically reveal the conditions under which the combustion is progressing in the reservoir, providing a real-time tool to influence the process by changing the necessary operating conditions that seem to have more influence.

Table 2 shows the average values of the main combustion parameters estimated for the whole project from February 2013 to December 2013. It is important to note the high O2 utilization and high % conversion of O2 to COx obtained, the saturation of fuel consumed less than 10%, and the relatively high volumetric efficiency, 27%, for the short period considered (11 months). These results indicate that the ISC process was preferentially dominated by HTO reactions.

Table 2—Average Combustion Parameters.

Average Combustion Parameters	Value
(CO2+CO)/N2	0.19
H/C Ratio	1.13
Efficiency of O2 utilization, %	93.3
Excess air,%	7.2
O2 conversion to COx (%)	77
Air-Fuel ratio, SCF/lbm fuel	193
Air requirement, SCF/ft3	304
Fuel content, lbm/ft3 rock	1.57
So_F, Equivalent sat. of fuel consumed, %	8.9
Rock volume burned, acre-ft	79
Rock volume burned, ft3	3,423,025
Total fuel burned, Bbl	16,016
Np displaced from burned zone, Bbl	49,054
Recovery Efficiency, unburned zone, %	30
Volumetric sweep efficiency (%)	27

On the other hand, Figure 11 presents some of the parameters computed on a well basis, averaged for the same time period. These graphs are essential to compare the process behavior in each well, which provides important input to understand and manage the operation. For instance, the discrepancies observed in the H/C ratio and N2 factor among wells indicates that the combustion is favored in some directions, something that had been anticipated after studying the heterogeneity of the formation.

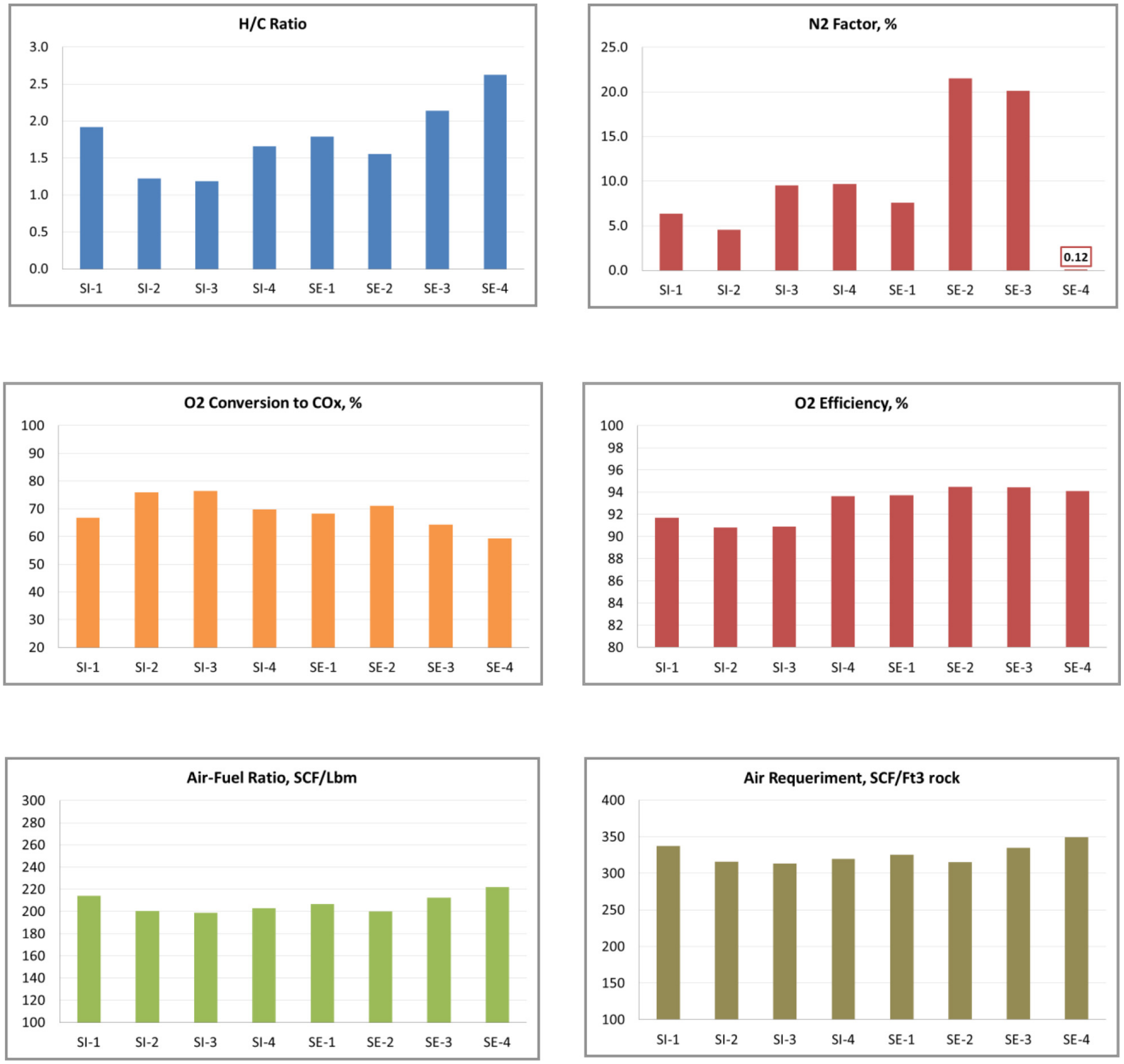
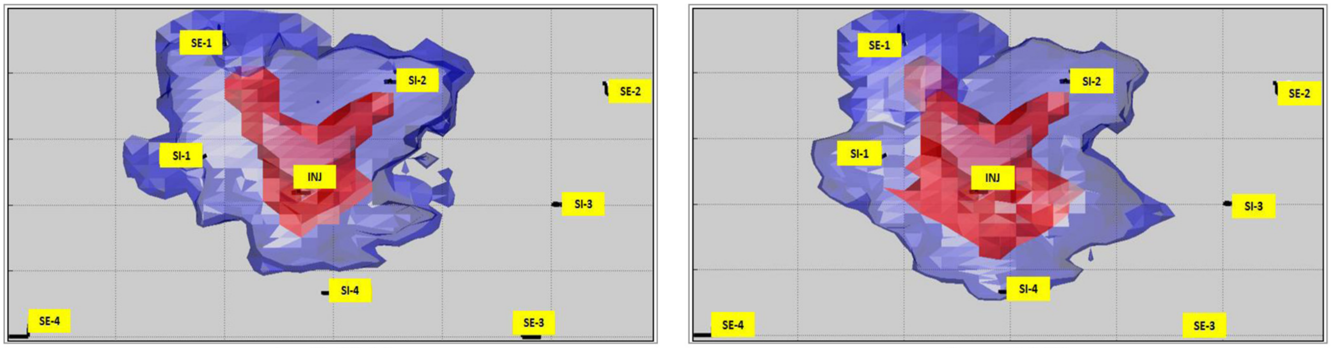


Figure 11—Average combustion parameters per well.

Finally, Figure 12 shows the changes in rock volume burned at different times, obtained with the *Intelligent Surveillance and Control of Combustion and Fluids Fronts* SM. As can be seen in the lower left hand side of Figure 12, the symmetrical shape in the rock-volume burned (red color) was obtained by manipulating well operational conditions, proving that the process was managed properly to achieve this. It is important to emphasize that these graphs were not just the result of a simulation run, but the SIM which also incorporates the data from each well and later on will include the 4D seismic.



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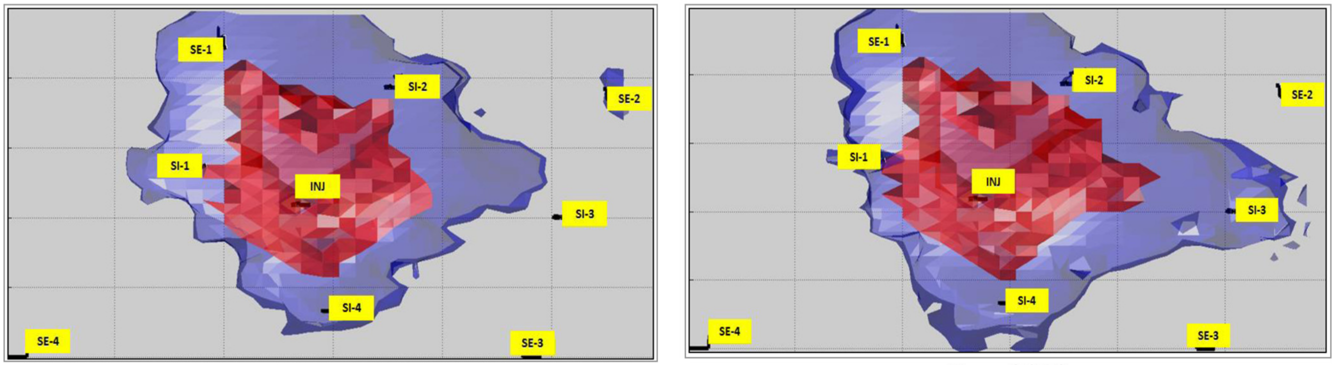

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Figure 12—Location and geometry of the combustion (red) and fluids (blue) fronts at different times.

Conclusions

1. The pilot was successful in recovering 30% incremental oil by the ISC process in less than 18 months. The combustion front generated was efficient in displacing oil.
2. The global gas composition observed, with high concentration of CO_2 and low O_2, indicates that HTO reactions were dominant during the combustion process.
3. The monitoring plan designed and implemented was crucial to properly and effectively carry out the pilot project, and was essential for understanding the ISC process in Quifa field.
4. The ISC process was identified as the most suitable technique for enhancing the recovery from fields with strong bottom aquifer like Quifa.

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The interpretations and conclusions expressed in this paper are solely those of the authors and not necessarily that of the organization.

Nomenclature

CH_4 = Methane
C_2H_6 = Ethane
C_3H_8 = Propane
CO_2 = Carbon dioxide
CO = Carbon monoxide
N_2 = Nitrogen

Np = Cumulative oil produced, Bbl
O2 = Oxygen
PRE = Pacific Rubiales Energy
So_f = Equivalent burned oil saturation, fraction
φ = Formation porosity, fraction.

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