ANTICIPATING OPERATIONAL ISSUES FOR THE FIELD PILOT TEST OF AIR INJECTION IN CHICHIMENE

H. García, E. Niz Velásquez, M. Trujillo
Ecopetrol S.A. – Colombian Petroleum Institute, Bucaramanga, Santander, Colombia

Colombia possesses 53 000 MBBL OOIP, from which 36 % corresponds to heavy and extra heavy oil. Out of this, 19 000 MBBL (70 %) are located in reservoirs at depths greater than 6000 ft. This fact makes mature EOR processes such as steam injection very challenging, forcing Ecopetrol to look for other alternatives to improve the recovery factor for this type of reservoirs.

In situ combustion is a technology widely tested through the history of the oil industry. With applications since the early 40th´s, there have been very successful projects around the world such as Suplacu de Barcau in Romania and Balol and Santhal in India with recovery factors above 50 %; however several failures have been reported due to both reservoir conformance and operational malpractices.

Chichimene in situ combustion pilot is the first attempt for Ecopetrol to incorporate this technology that could be applied to at least 80 % of its heavy oil assets. It is important in every stage of the process to determine the possible operational issues that may come with the technology in order to establish the procedures and strategies to either avoid or mitigate the impact that these factors may have in the success of the test. Through analogy analysis as well as experimental tests run in the laboratory, a risk characterization and analysis was carried out and the most critical problems were identified for our specific case.

The Colombian Petroleum Institute of Ecopetrol then established four lines of research, one for each of the issues with high probability of impacting the Chichimene pilot: (1) Materials integrity for both bottom hole and surface equipment due to corrosion; (2) Characterization, preparation and treatment of emulsions from the in situ combustion process; (3) Temperature impact on sand consolidation; (4) Analysis of injectivity and connectivity through the target formation.

Keywords: in situ combustion, heavy oil, operational issues, emulsions, corrosion, sand consolidation, injectivity, connectivity

DOI: 10.18599/grs.18.4.6

For citation: García H., Niz Velásquez E., Trujillo M. Anticipating operational issues for the field pilot test of air injection in Chichimene. *Georesursy = Georesources*. 2016. V. 18. No. 4. Part 1. Pp. 289-298. DOI: 10.18599/grs.18.4.6

Introduction

In situ combustion (ISC) is a process that consists on injecting air into the formation to generate a combustion front by a series of chemical reactions, where the heaviest hydrocarbons fractions are burned as combustible. These reactions are considered exothermic, which by means of increasing temperature, decrease oil viscosity, increasing the mobility of the crude, resulting in improved production and access to more reserves, representing an interesting option for the heavy oil reserves in Colombia.

The Chichimene field is located in the southwestern edge of the Llanos Basin, in Colombia, south of the town of Villavicencio, in Meta department (Figure 1). This field was discovered in 1969 and started its production in 1985. The current field production is close to 80 000 bpd with an Estimated Ultimate Recovery (EUR) by primary means of nearly 9 %. The formation of interest in this study produces heavy oil of 8° API from the Tertiary unit (San Fernando formation – T2). The field structure is associated with an elongated and asymmetric anticlinal, faulted on the eastern flank in direction N60E approximately. The in situ combustion pilot is located towards the structure's crest and exhibits low dip values (2° approximately) (Gómez, 2013).

The ignition is scheduled to occur at the end of 2016. Although ISC has not been applied before to extra-heavy oil reservoirs at such depths (8 000 to 9 000 ft), the high reservoir temperature (200 °F) is favorable for spontaneous ignition, and sufficient oil mobility enables the application of the process.

Other large reservoirs bearing a significant fraction of the Colombian oil resource exhibit characteristics similar to Chichimene.

This shows the potential for the expansion of ISC in Colombia, and eventually in other countries, as the technology boundaries are pushed further away than its current applicability limits.

Ecopetrol has partnered with renowned companies, universities and consultants with relevant experience in ISC. Currently, a state-of-the-art ISC laboratory operates at the Colombian Petroleum Institute, and capabilities for numerical modelling of the process have been developed.

The Chichimene in situ combustion pilot

The ISC pilot at the Chichimene field is made up of a single injector well (CH-174), two observer wells (CH-172 and CH-173), and three first-line producer wells (CH-95, CH-96 and CH-97). The first line wells are located at an approximate distance of 120 m from the injector well, forming an area of approximately 10 acres. Additionally, a second row of producers (the wells closest to the first line wells) are going to be included in the monitoring strategy with the objective of evaluating the influence of the process on these wells. Schematics of the geometrical distribution of the pilot wells are shown in Figure 2.

The sedimentary sequence of T2 stratigraphic unit, presents a high degree of lateral continuity in the pilot area. From the operational view point, this unit is subdivided into eight subunits, which are easily identifiable in the area due to the high correlation degree resulting from this type of sedimentary environments (Figure 3).

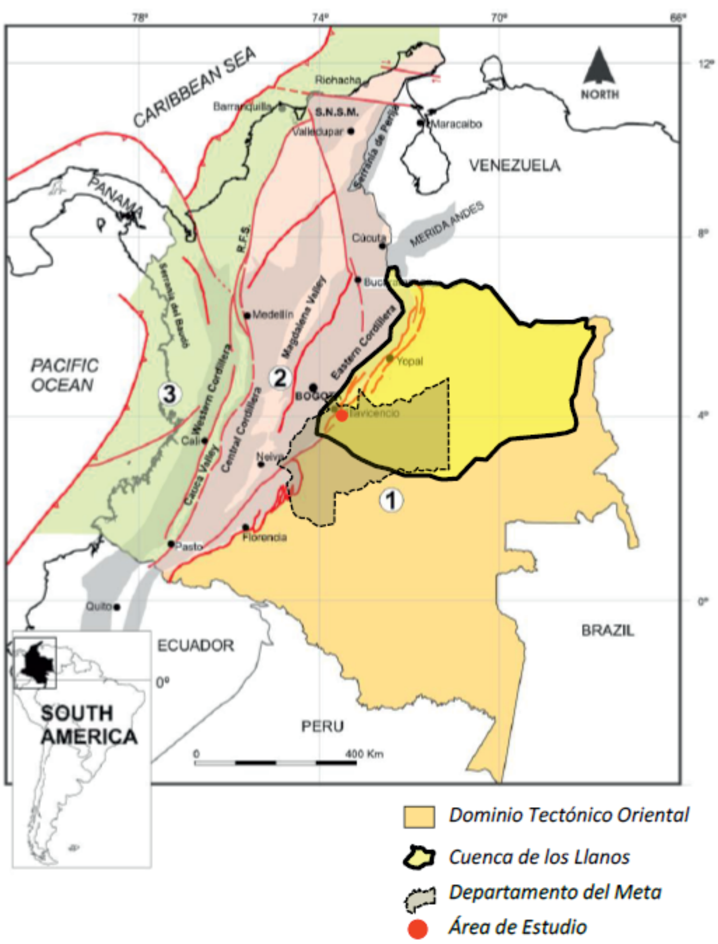

Figure 1. Chichimene field location map.

One of the closest second-line wells is producer CH-22. A fault separates the pilot area with the block where CH-22 is located and a structural jump of 140 ft compartmentalized the pool. However, there is sand-to-sand contact between the T2_40 unit at the injector block with the T2_60 unit at the CH-22 block, which suggests that the fault is not sealing (Figure 4).

It was assessed that two years would be sufficient to evaluate the performance of the ISC process. Numerical predictions yield incremental recovery close to 35 % OIIP. Ongoing activities of the pilot project include detailed laboratory studies and ignition predictions for preparedness.

Analisis of the most common operational issues in in situ combustion projects

Throughout the world many in situ combustion projects have been implemented in time, and most recently, due to the advancements in material integrity capabilities and the chemical characterization behind, the process is becoming a more attractive technology for heavy oils.

Table 1 presents the most common operational issues for in situ combustion projects reported in literature (Arias, Rodriguez, 2013).

After revising around 38 projects carried out from 1958 until 2013 (Arias, Rodriguez, 2014), it was found that the most impacting operational problems for in situ combustion are:

1. Incrustations: there are three facts associated with the air injection process that can lead to the appearance of incrustations (Crabtree et al., 1999):

- Incompatible mixtures between water injection and water reservoir when a wet process is implemented.
- The auto sedimentation by changes of temperature and pressure experienced by the reservoir fluid during

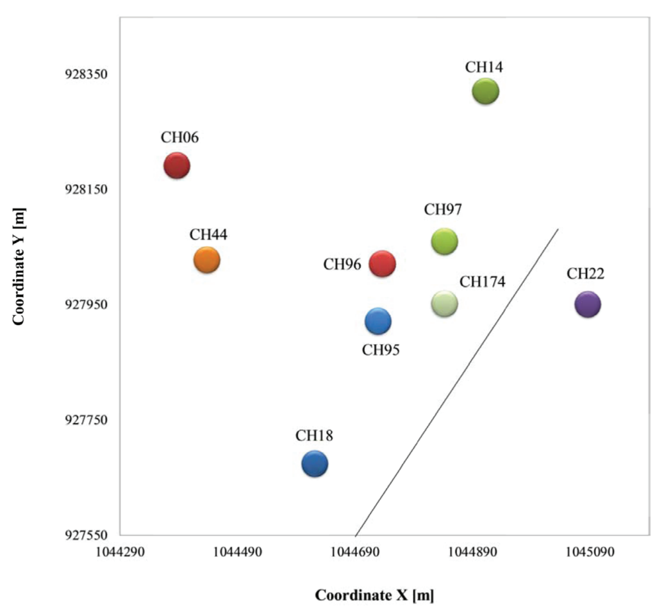

Figure 2. Schematics of the geometrical distribution of the pilot wells.

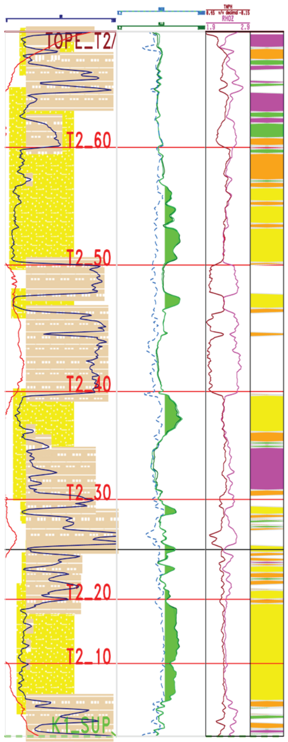

Figure 3. Sub-units of T2 formation.

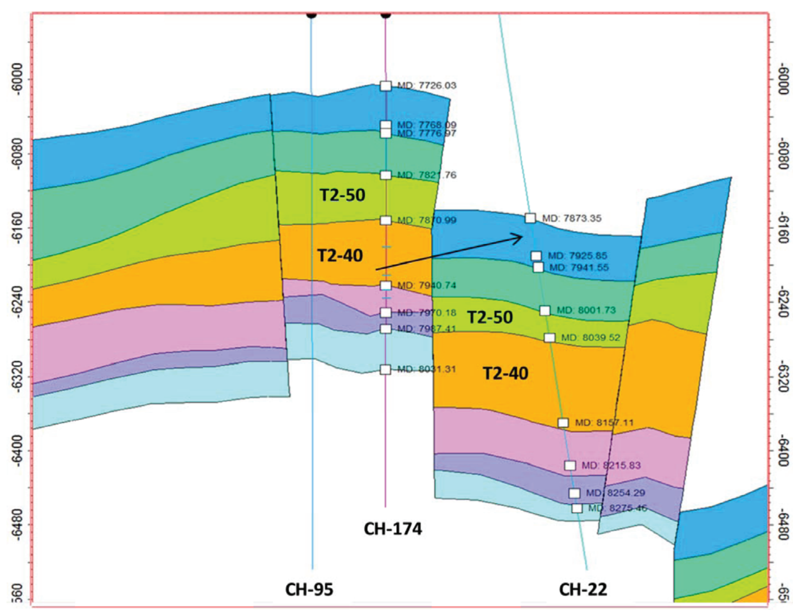

Figure 4. Fault between wells CH-174 and CH-22.

production, which modifies its composition such that the solubility limit of a certain mineral is exceeded and this precipitated as mineral encrustation.

- Release of combustion gases (CO_2): Water containing CO_2 becomes acidic and dissolves calcite found in the formation. Subsequent pressure drops that occur in the wellbore producer may cause the CO to be separated from the solution and precipitate carbonate residues, which causes additional pressure drop and therefore more precipitates leading to a decrease in well productivity.

2. Asphaltene precipitation: during the implementation of air injection processes, pressure, temperature and crude oil composition changes occur, which may cause asphaltene precipitation that can affect the porosity and permeability of the reservoir (Creek et al., 2007).

3. Sand production: can be expected at any stage during a production well life and happens mainly due to a mechanical failure associated to the resistance and the effective effort applied to the formation. It is a very common phenomenon on unconsolidated shallow sands. However, high temperatures experienced in the reservoir during thermal recovery methods can cause formation matrix cement loss, generating sand movements within the reservoir and sometimes to the well, causing serious blockage and compromising productivity. During in situ combustion implementation this issue can arise due to the following factors:

- Temperature increasing, which weakens the cement material of the matrix, causing resistance loss and then sand movement. Additionally, temperature rise may cause casing detachment and collapse.

- Flux rate increase causes fluids dragging and then more solids would move towards the production well (Gonzalez, 2005).

Excessive solids production can generate restriction in the fluid production rate and equipment may need replacement due to erosion.

4. Emulsions: generally speaking they are most likely found in presence of an emulsifier agent and enough energy for the emulsion to form. They can be found in any process during crude extraction. In presence of sand or corrosion the problem tends to worsen. For the case of the in situ combustion process, formed emulsions are very stable water-in-oil ones (Pineda, 2009). Factors influencing emulsions formation during in situ combustion are:

- Low temperature oxidation reactions, present during early combustion front formation. These reactions add components to the crude superficial activity that encourages the formation of emulsions. Crude oxidation decreases interfacial tension which contributes to the emulsions' stabilization (Mourits, Coulombe 1989).

- CO_2 formed during combustion can cause crude resines and asphaltenes colloids precipitation.

- Corrosion products such as Iron sulphides encourage emulsions stabilization.

- Condensed steam ahead of the combustion front present either in the formation or production facilities can be stabilized by micronic and submicronic drops from the emulsifier agents.

- Turbulent flux energy increase and the gas freed from the fluids in the reservoir can create emulsions as well, which are stabilized by the emulsifier agents created during combustion.

Problemas / Campos	Incrustations	Paraffins and / or asphaltenes	Sand production	Low injectivity	H2S and CO2	Emulsions	Corrosion
Balaria						x	
Balol			x	x	x		
Bellevue			x			x	x
Brea Olinda Ca				x			
Carlyle						x	
Countess	x			x			x
Esperson						x	x
Fosterton Northwest, Sask				x			
Hospah						x	x
Kyrock						x	
Lloydminster			x				
May Libby, La				x		x	x
Mene Grande			x				
Midway Sunset, Ca			x	x			x
North Tisdale	x			x		x	x
North Ward estes					x		x
Pauls Valley			x		x	x	x
Robinson Fry, Il						x	x
Schoonebeek, The Netherlands		x		x			x
Sloss, Ne						x	x
South Hospah						x	x
Suplacu de Barcau				x			
West Heidelberg							x
West Texas				x			

Table 1. Most common operational issues for in situ combustion projects.

5. Low injectivity and connectivity: due to the presence of organic and inorganic deposits. It is directly related to permeability and porosity, and inversely proportional to fluids viscosity present in the porous media. During the coke formation in the combustion process, porous media can be blocked, changing the preferential path to the production wells. Other problems such as sand production and emulsions can influence on the injectivity and connectivity of the system.

6. Mechanical failures: due to the high temperatures at which the cement is subjected during the process, it suffers loss of strength and changes as empty spaces between the formation and the cement are generated, which in turn allows free movement of casing and it can cause pipe buckling or collapse. Similarly, thermal processes can have several effects on both the casing and production pipe, such as buckling, erosion, stress, corrosion and melting.

7. Corrosion: generated by high temperatures in the bottomhole, oxygen in the producer well due to channelling or incomplete combustion, CO_2 and H_2S dissolved in water, wet air injection, products of some oxidation reactions, among others.

8. Channelling presented mainly by the presence of areas with greater permeability leading to early air irruption in the producer wells and therefore to a decrease of process areal sweep efficiency.

9. Compressors explosion and damage due to high temperatures, high vibration and excessive noise which creates unfavourable conditions for the system. Generally, the causes of these failures are the long operational life of the equipment and lack of maintenance.

Risk analisis and operational issues characterization for in situ combustion in Chichimene field

Using probabilistic methodologies, the operational issues were analysed in order to determine their impact and the chances of occurrence in order to focus resources on researching for mitigation and solution of the most threatening ones for the Chichimene pilot.

A qualitative risk analysis was carried out in order to first identify the most common issues reported in in situ combustion projects with similar characteristics to Chichimene field, second to evaluate their impact, and finally to estimate these issues' occurrence. The impact was evaluated taking into account process efficiency, production time loss, production volume loss, non-environmentally friendly substance release and economy. Figure 5 shows the qualitative analysis.

As seen in the figure the most critical operational issues were corrosion, emulsions, low injectivity-connectivity followed by sand production and H_2S and CO_2 production.

Following the risk analysis, a cause-effect analysis was performed in order to determine the relationship among the parameters influencing the main operational issues. In this way it is possible not only to graphically understand the most important parameters and issues but also to stablish solutions and mitigation strategies that can treat several issues as the cause is evident and it may be the source of more than one issue. Figure 6 presents an integrated cause-effect diagram for the analysed issues.

According to the perform analysis and the comparison between Chichimene field parameters and the parameters revised from the other in situ combustion projects, it is concluded that corrosion is the most critical issue that the in situ combustion pilot in Chichimene may face, as out of the operational ranges compared in the risk and the cause-effect analysis, 85 % of the parameters that contribute to this issue are present in the Chichimene case. For example, formation temperature for Chichimene is around 185°F and the temperature range for fields experiencing corrosion is between 65 and 221°F. The following issues were: corrosion, emulsions, sand production and injectivity – connectivity inferred the highest percentage compare to the other projects having these issues.

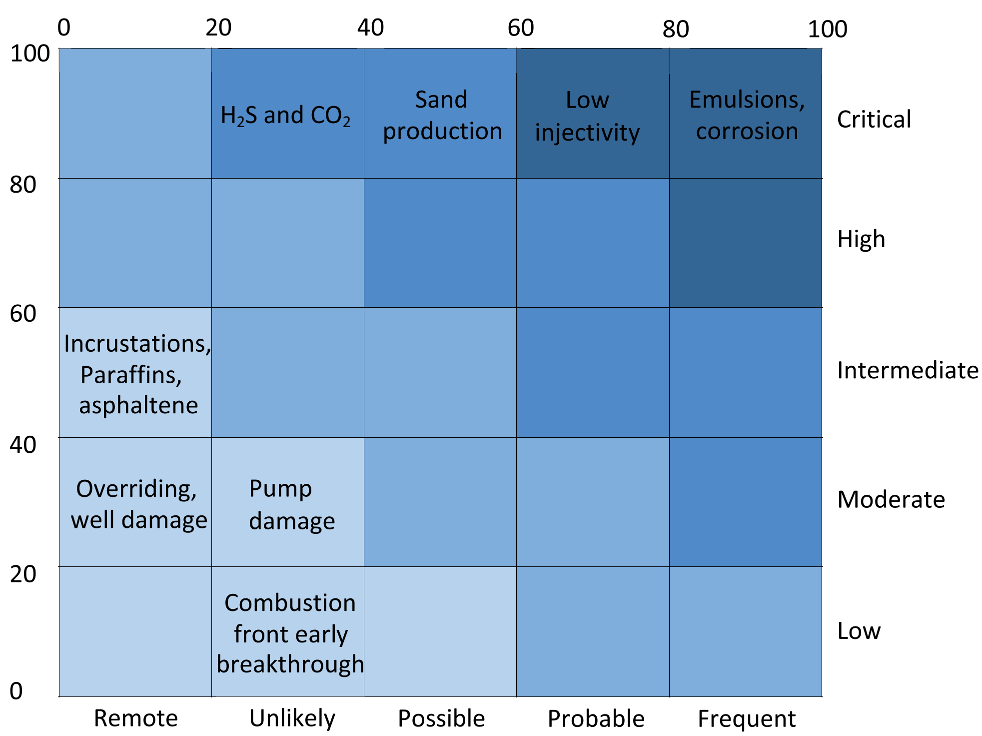

Figure 5. Qualitative analysis. Source: Arias, Rodriguez, 2013.

Ecopetrol stablished then four lines of research in order to characterize analyze, and stablish mitigation and control strategies for these four specific issues. However the monitoring and control strategy for the in situ combustion pilot includes all the possible issues observed in previous projects and the ones expected through the laboratory and simulation analyses performed throughout the project implementation.

The research were focused on these main topics: (1) Materials integrity for both bottom hole and surface equipment due to corrosion; (2) Characterization, preparation and treatment of emulsion from the in situ combustion process; (3) Temperature impact on sand consolidation; (4) Analysis of injectivity and connectivity through the T2 formation.

1. Analysis and selection of suitable alloy materials for the in situ combustion process

The first step in the feasibility analysis for in situ combustion implementation is the set of laboratory tests: RTO (Ramped Temperature Oxidation), ARC (Accelerating Rate Calorimeter) and Combustion Tube Test. These experiments were carried out with reservoir crude oil and rock. For the analysis, brine was synthetically prepared in the laboratory trying to match the chemical composition of the brine from Chichimene T2 formation field

Each of these tests provides information regarding rock-fluids reactivity, kinetic of the oxidation reactions, and finally the percentage of each product detected during the process. The chemistry of the reactions includes CO_2, CO and H_2S production as well as the Oxygen introduced during the process. With these data an experimental design and the materials selection process was established.

In 1985 R. Zawierucha studied the behavior of several materials used for the in situ combustion process, indicating that the materials selection for this type of technology must be supported by laboratory and field tests taking into consideration the following:

1. Lab scale tube test immersion of several alloys over a wide temperature range and aggressive environment composition.

2. Electrochemical analysis.

3. Field tube test immersion with bottom hole coupons of different alloys for both production and injection wells.

The corrosion phenomena in oil fields are generally associated to the presence of CO_2 and H_2S, however diluted oxygen is another agent rarely found at reservoir conditions but common for reservoirs undergoing water or air injection such as in situ combustion. Affectation for H_2S is hard to predict because the iron sulfide (FeS) produced by corrosion is normally insoluble at regular pH, and can form a film that protects the material. In presence of carbon dioxide (CO_2) the pH experiences a decrease and then the iron sulfide becomes more soluble. Oxygen in presence of H_2S and CO_2 accelerate the corrosion process.

Historically, the in situ combustion projects found in the literature show a common characteristic: they all possess well infrastructure designed with conventional materials with P110 and N80 steels. Materials with better behavior include special alloys with high cost such as Incoloy, Inconel and Hastelloy, which can reach negligible corrosion values of an order of 0.025 mm/yr (1 mpy); however from an economic feasibility point of view it can become non profitable for the project development specially when it comes to a pilot level as Chichimiene. Some other alternatives include Chromium alloys that offer bigger resistance to several corrosive environments, especially the ones with Chromium content greater than 12 %.

Chichimene in situ combustion pilot presents conditions of 0.6 % of H_2S (6 000 ppm) and 15 % CO_2 molar concentration (150 000 ppm), that added to the depth, API gravity and temperature must be considered critical and particular for the project, making it hard to be referenced with previous in situ combustion projects in the world. These conditions represent a wide uncertainty for the definition of the suitable materials for casing and tubing, as well as the piping and equipment for the surface treatment facilities.

Bottom hole materials selection

Based on the operational and fluid composition conditions taken into account for the reservoir simulation, and the lab results of the combustion tube tests, simulation parameters were established for simulating the mechanical properties and the corrosion

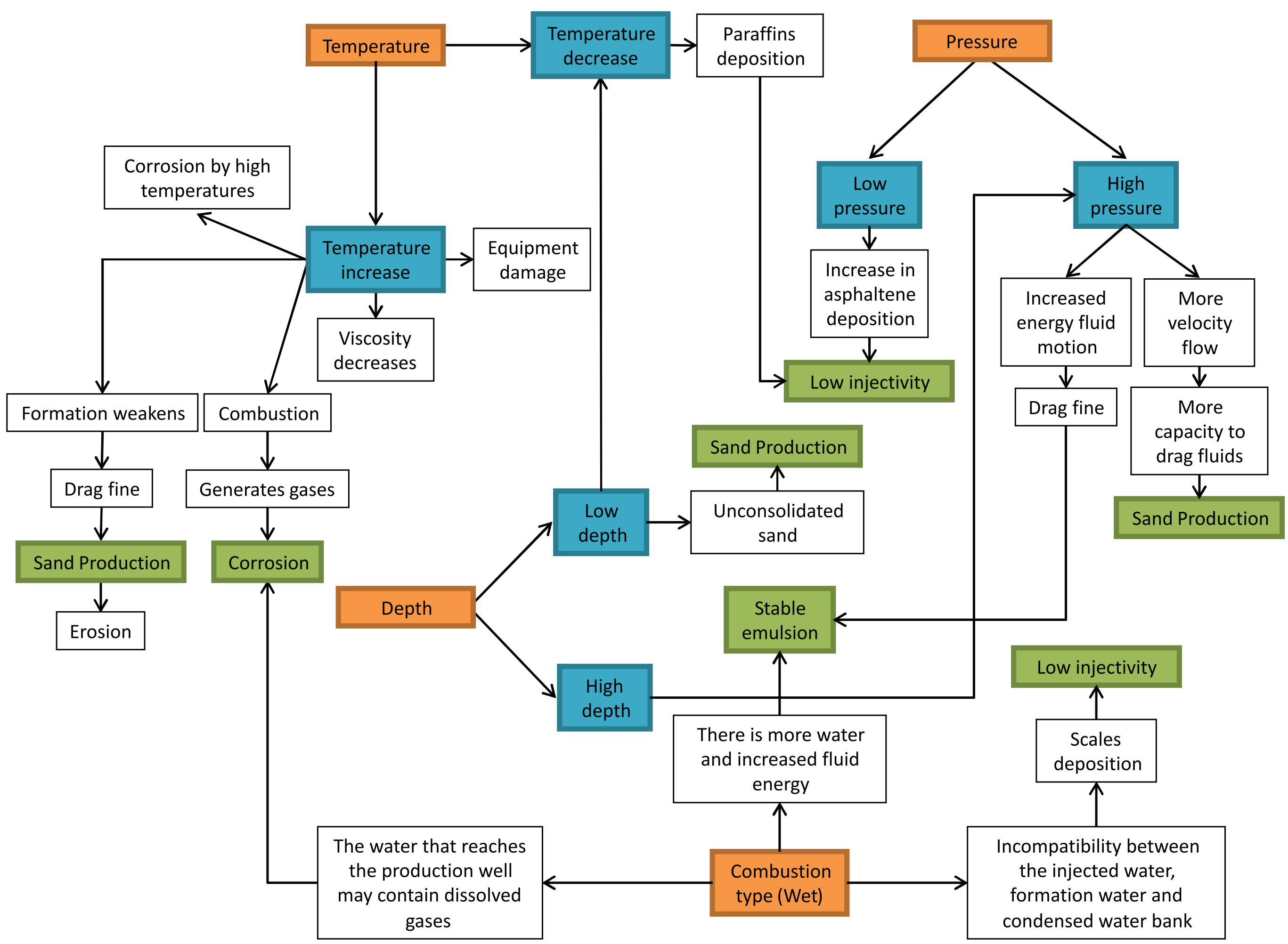

Figure 6. Integrated cause-effect diagram. Source: Arias, Rodriguez, 2013.

resistance of alternative materials for these conditions such as chromium alloys (13 % Cr), low alloy carbon steel, corrosion resistant alloy nickel based, and sour service steel. This simulation analysis was technical supported by Tenaris Tamsa of Mexico, through their software Osprey and Matsel, suitable for mechanical and corrosion conditions analysis respectively.

The mechanical parameters analysis allows one to determine that the common materials used for this purpose such as N80, P110 and Q125, including the ones with Chromium alloy are suitable to be implemented for the in situ combustion process.

The corrosion resistance analysis however, showed a bigger restriction in the usage of all the alternatives. The most critical condition observed through the corrosion resistance analysis is definitely the H_2S concentration due to the high susceptibility of its presence as SSC (Sulfate stress cracking) mechanical damage. Additionally, the analysis showed low CO_2 corrosion velocity values, probably as a consequence of the API gravity. The heavy oils with low gravity considerably minimize CO_2 corrosion as the corrosion products themselves ($FeCO_3$ and FeS) act as protection barriers.

Based on the operations parameters analysis, the literature review and the simulation analysis, where the most critical operation parameters was determined to be H_2S content, it was possible to establish the usage of materials manufactured to work in acid environments (sour services), which could perform more efficiently.

With these results, the integrated analysis was focused on verifying the materials suitability under mechanical resistance properties. In order to confirm the viability of using these type of materials with lower tension resistance, a more extensive mechanical properties analysis was performed. Several simulation analyses were run using higher safety factors compared to the industry standards. As a result, steel alloys with special manufacture for higher impurities control levels (99.9 % impurities free), is the most suitable for the process in Chichimene when it comes to bottom hole casing and tubing, as they offer a better performance for sour service based on the following aspects:

- Prevention in advance of any corrosion attack by SSC.

- Low chance of CO_2 corrosion attack, as the low API of the crude minimizes its effect on the materials.

- Usage of high safety factor for the design to ensure integrity of the well in case of any casing or tubing slimming.

Surface facilities material selection

The big challenge when it comes to surface equipment is the materials integrity preservation of static equipment given the critical conditions due to strongly-acid environments handling, which result on interior and exterior corrosion threats.

Interior corrosion refers to corrosion phenomenon that occurs inside the piping or structure, where there is an interaction between the material and its environment resulting on a material degradation. Corrosion under efforts and strongly-acid environments such as H_2S presence is known as a damage mechanism of assisted cracking typically found on highly resistant steels, only under certain effort conditions. SCC involves effort application, perpendicularly applied under partial pressure of H_2S higher than 0.34 KPa (0.05 psia). This damage mechanism results from the atomic hydrogen adsorption generated in the cathodic area by the sulfur corrosion acting over the surface material.

Exterior corrosion refers to the phenomenon that causes physical degradation or cracking due to the material surface interaction with external environment (air/soil). It can happen as a uniform material loss, or as a localized or isolated material loss or environmentally assisted cracking.

Based on this corrosion phenomenon, a simulation work is carried out, and through laboratory test each of the threats is analyzed under the operational parameters established during the design stage. These evaluation results allow establishing the materials susceptibility and their classification in the severe, high, moderate or low corrosion range according to the criteria included in the practicum standard NACE SP0775.

Corrosion threat by mechanical efforts from H_2S environments is one of the most critical ones for materials in a in situ combustion project, and it is important to take into account NACE MR0175 and API 57 norms in order to determine material susceptibility to SSC. In relation to the exterior corrosion, it must be monitored mainly for the buried infrastructure. For this purpose is necessary to estimate environmental parameters such as conductivity, humidity, texture, pH, sulfates, carbonates, acid number, resistivity and determination of sulfate / thiosulfate reducing bacteria.

Corrosion mitigation and management strategy

Having the threats and their impacts characterized, it is important to determine the actions to be taken in order to avoid materials inconvenient that could jeopardize the in situ combustion test success. First of all these analysis must be carried out prior the design stage, as it is important to design at required specifications to handled corrosive environments. Further actions include control and mitigation alternatives for the infrastructure, both bottomhole and surface facilities for each of the found threats:

1. Interior corrosion: materials selection, chemical treatment injection, corrosion monitoring (coupons,

tube test, water, crude and gas physicochemical analysis).

2. Corrosion under H_2S environment efforts (SS): materials selection, chemical treatment injection, SSC monitoring (including coupons, water, crude and gas physicochemical analysis).

3. Exterior corrosion: coating, cathodic protection systems.

Additionally it is important to perform a risk based inspection (RBI) for both wells and surface facilities with the objective of understand, identify and control risks associated to the pipes and equipment operations in order to optimize resources on infrastructure maintenance. For the surface facilities, the RBI is based on the initial design, simulation and operational parameters concept and criteria, from where the damage mechanisms are identified. For the bottomhole equipment the RBI is based on the operational conditions simulated, the mechanical design concept and criteria, that allow to identify and value the risk level as well as the most critical failures for the mechanical integrity of wells.

2. Characterization, preparation and treatment of emulsions from the in situ combustion process

Tight water-in-oil emulsions have been observed in field applications of the in situ combustion process. Crude oxidation at low temperatures (LTO mode: Low-Temperature Oxidation) results in an increased concentration of emulsifiers in the oleic phase (Turta et al., 2005). In this line of research, a strategy for dealing with this potential issue was set, and is described as follows:

1. Chichimene crude oil samples are subject to oxidation in a continuous flow reactor at conditions representative of the LTO region.

2. Synthetic emulsions are produced by mixing the oxidized crude oil with formation water at high energy.

3. The synthetic emulsions are characterized by describing their reological properties, Z-potential, abundance of functional groups (by mass spectrometry techniques) and water droplet size distribution.

4. Field samples (emulsions) are taken in an analogue field subject to in situ combustion, and characterized as described in the previous step.

5. The synthetic and field emulsions are compared and common compounds and physical properties are identified.

6. Combined treatment methodologies are proposed and tested in the laboratory, including dilution, chemical additives, heating and electrostatic means, for both synthetic and field emulsions.

The optimal temperature and flow conditions in the continuous flow reactor that led to stable water-in-oil emulsions were identified to be consistent with the LTO ranges. The characterization efforts evidenced chemical and physical similarities between the two types of emulsions. The treatment tests allowed identifying viable options for breaking the emulsions using the existing surface facilities.

3. Experimental study of temperature impact on sand consolidation for the in situ combustion process

Sand production during thermal recovery processes is a very common problem due to the high temperature in the reservoirs that affect the cements matrix and the mineralogical composition, as well as high flux velocity that encourage particules migration towards the production wells.

With the purpose of determining in advance the effect of these parameters in the in situ combustion implementation for Chichimene, geomechanical, mineralogic and morphologic analyses were carried out. These analyses focused on evaluating the sand consolidation response to mechanical efforts produced by the high temperature released by the oxidation reactions during the in situ combustion process. For the analysis several rock samples were exposed to several thermal treatments simulating the in situ combustion operational parameters to be observed during the pilot operation.

The developed methodology included sample interval selection point according to lithotype's identification, petrophysical analysis, morphological and mineralogical characterization through CMS (Confining Measurement System), SEM (Scanning Electronic Microscopy) and XRD (X Ray Diffraction), granulometric distribution and unconfined compression. The purpose of these analyses is the following parameters determination: Young module, poisson relationship, internal friction angle, mineralogical and morphological composition, porosity, permeability and rock grain density.

From these analyses it was evident the necessity of further experimental tests increasing the exposition time to temperature treatment in order to reply reservoir conditions under temperature exposition for long periods like it happens during combustion front advance. The punctual temperature exposition used for this first experimental attempt produced incoherent results between basic petrophysical analyses and the other techniques. However the results from the other tests showed encouraging results: mineralogical and morphological changes, low organic material loss, minor porosity changes in the combustion front surrounding area, stable Young module (changes under 5 %) and not significant Poisson relation changes (less than 10 %). These results indicate a moderate affectation to sand consolidation but in the combustion front area. The flux velocity is not big enough to drag fines all the way to the production wells.

Another important aspect from the analysis is the seal rock evaluation. The analysis showed a resistance increasing with temperature for the seal rock type 1. Seal rock type 2 didn´t show variation through XRD analysis, however it logged a shale content decrease after heating treatment with no impact in the T2 sand consolidation and process isolation within the target zone.

4. Analysis of injectivity and connectivity through the T2 formation

A short water injection test was carried out in injector well CH-174 soon after its completion, corroborating the order-of-magnitude estimate based on the petrophysical and geometrical properties of the well and formation. According to these figures, the design gas injection rates would be injected without producing pressure gradients that would in any case affect the operating ranges of the injection-production system.

The nitrogen connectivity test (NCT) was designed to have an approximate duration of three weeks. The aim of the test was twofold: 1) To determine the response of the injection-production system to the displacement of a compressible fluid through the formation, and 2) To identify flow patterns that would shed light on the appropriateness of the geometrical design and well configuration of the pilot.

A monitoring strategy was designed to obtain as much information from the NCT as possible. Four stages were identified for the sake of monitoring: 1) A baseline, a week before the nitrogen injection, to have a high-resolution zero line for gas rate, bottom hole pressure and gas compositions, 2) Detecting nitrogen breakthrough at the first-line producer wells (CH-95, CH-96 and CH-97 as seen in Figure 2), with frequent monitoring of artificial lift system parameters and gas compositions in these wells, 3) Redirecting nitrogen flow resulting in the most uniform distribution possible, using data and controls at the first-line producers and injection wells, and 4) To detect nitrogen breakthrough at the other surrounding producer wells.

Figure 7 summarizes the designed versus actual duration of each of the above-described stages. Nitrogen took longer to arrive at the three producer wells than anticipated by reservoir simulation. Uncertain parameters will need to be consistently adjusted in the simulation model to match this behaviour. However, the breakthrough times were very similar, occurring within 48 hours of each other, evidencing a uniform progression of the nitrogen front within the pilot volume. The homogenization stage lasted only three days, limited by the erratic performance of the artificial lift system under higher producing gas-liquid ratios, which ultimately resulted in shutting in the first-line producer wells and extending the monitoring time at the producers beyond. The monitoring was extended for longer than two

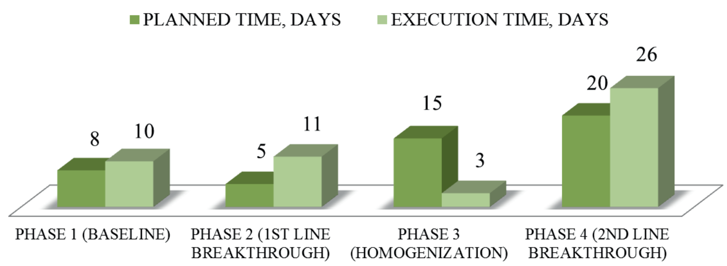

Figure 7. Duration of each of the NCT phases: Planned versus Executed.

weeks before the end of nitrogen injection. There was no nitrogen detected at any second-line well producer while the first-line wells were open.

The nitrogen transit times in the reservoir were found to be correlated with the distance between the injector and each producer well in all directions. This evidences a very favorable scenario for air injection, since reflects that the T2 formation is homogeneous in the pilot area and beyond. This observation was true even for the well CH-22, which is located at the other side of a fault in a sunken block (Figure 4). Reservoir simulations did not predict an early nitrogen appearance at this well, and the model needs to be updated for a better connectivity in this direction. These adjustments in the simulation model are crucial for a more effective prediction and monitoring during the in situ combustion.

In terms of the operational performance of the system, adjustments are needed in the artificial lift design, in order to avoid failure due to high gas production rates.

Summary of findings and final thoughts

In order to manage possible operational issues during the in situ combustion pilot test, it is important to carry out a series of experimental analysis. These experimental tests must be focused on characterizing the expected operational problems and then establishing mitigation and management strategies that diminish the impacts on the success of the process implementation. For the case of Chichimene, the most critical issues expected are corrosion, emulsions, sand production and lack of injectivity-connectivity. For each of these issues a monitoring and mitigation plan was established; however only during the pilot operation their real impact on the process will be verified.

Acknowledgments

The authors wish to thank the Chichimene in situ combustion pilot team in Ecopetrol. We also thank the team of consultants and allied companies and institutions that have partnered with Ecopetrol throughout the pilot project, including: Alex Turta, Anthony Kovscek, Claude Gadelle, Gordon Moore, John Belgrave, Louis Castanier, Marco Thiele, Margot Gerritsen, Olivier Clause, Raj Mehta and representatives of ONGC and UIS.

References

Arias, A, Rodriguez, C. Alternativas para los problemas operacionales críticos durante la implementación de un proceso de combustión in situ en un campo de crudo pesado en Colombia. Universidad Industrial de Santander. Bucaramanga. 2013.

Crabtree, M, et al. La lucha contra las incrustaciones – Remoción y prevención. En: Schumberger [en línea]. 1999. http://www.slb.com/~/media/Files/resources/oilfield_review/spanish99/aut99/p30_49.pdf.

Creek, J, et al. Los asfaltenos: Problemáticos pero ricos en potencial. En: Schumberger [en línea]. 2007. http://www.slb.com/~/media/Files/resources/oilfield_review/spanish07/aut07/p22_43.pdf.

Gómez, R. Evaluación de la factibilidad técnica para la implementación de un monitoreo sísmico en un proceso de combustión in situ, caso de estudio, Cuenca de llanos, Colombia. Master thesis. Universidad Industrial de Santander. Bucaramanga. 2013.

Mourits, F, Coulombe, S. Separation and characterization of surfactants presents in emulsions produced in thermal recovery process. SPE SS-89-24. 1989.

Pineda, C. Guía laboratorio de fluidos. Identificación y tratamiento químico de emulsiones. Bucaramanga. 2009.

Turta, A.T., Chattopadhyay, S.K., Bhattacharya, R.N. et al. Current Status of the Commercial in Situ Combustion (ISC) Projects and New Approaches to Apply ISC. Paper SPE 2005-002. *Canadian International Petroleum Conference*. Calgary, Alberta, Canada. 7-9 June, 2005. http://dx.doi.org/10.2118/2005-002-MS.

Zawierucha, R. Materials Performance in Thermal Enhanced Oil Recovery Environments. *The Journal of Canadian Petroleum*. Ucc-Linde Division. Montreal. REVISTA.1985

Information about authors

Hugo García – Petroleum Engineering, M. Eng., Research & Development EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta

Phone: +57-76847392

E-mail: hugo.garcia@ecopetrol.com.co

Eider Niz Velasquez – Petroleum Engineering, PhD Research & Development, EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta

Phone: +57-76847598

E-mail: eider.niz@ecopetrol.com.co

Martha Trujillo – Petroleum Engineering, MSc Leading in EOR Department, Ecopetrol S.A. – Colombian Petroleum Institute

Colombia, Santander, Kilometro 7 vía Piedecuesta

Phone: +57-76847158

E-mail: martha.trujillo@ecopetrol.com.co

Manuscript received October 20, 2016