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Reservoir Study V9 of El Furrial Field, Venezuela

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Abstract

El Furrial field is one of the most important hydrocarbon giants of Venezuela. It's located at the north of the Monagas State and it handles approximated 45 % of the production of this area. It was discovered in 1986 and its characteristic makes it unique. The strategy of development has been supported by the combined injection of miscible gas and water, this has allowed to maintain the production plateau of 400 MBPD. A previous feasibility study showed a recovery factor ranging from 50 % to 60 % by implementing AGA, that study lead to the necessity of a new numeric model capable of simulate non conventional recovery possesses, creating a model known as the V9 Model.

This new approach is one of the most transcendental advances of the El Furrial field characterization. It's created over a structural model, which is based in 3D seismic of 370 Km2., which allowed a better definition of structural complexity. A petrophysics supported by 13692' of core, classified by 5 types of rocks, representing the heterogeneity of the reservoir. A high resolution stratigraphics model which is based on a cronostatigraphic criterion, which defined 47 statigraphic units. A sediment model based on 24 Paleoambient maps, considering direction of the sediment in the geostatistic model. A fluid model which changed a TarMat surface that varied from a horizontal to a folded one. A Geocellular model which is described by a 350 million cells grid, which generated a simulation grid of 500K active cells out of 900K.

A thermodynamic model which honors the fluid model, with a miscible option validated by a slim tube and iswelling tests and a state equation for the compositional simulation. A rock-fluid model with a set of curves per rock type, which considers the hysteresis process that allowed simulate the AGA and the Dewatering process.

As a result the OOIP increased in 1.3 MMMBls. A fluid model with thicker and area extension of the TarMat in the sands. Drilled new delineation wells in areas previously considered in the non-economic limit incorporating new reserves and the development of new opportunities. A portfolio of 70 locations for the development of reserves of the field. Modeling of an AGA pilot project in order to evaluate the implementation of it. Evaluation different injection processes conventional and non conventional, in order to define the development plan of the field. The integrated subserface-surface simulation achieving the integration between recollection and the reservoir model V9, which is one of the biggest world wide.

Introduction

"El Furrial" field is located North of Venezuela and was discovered by the well FUL-1 in February 1986 (Fig. 1). The field produces from two main formations identified as the Naricual and Cretaceous Formations. The gross thickness of the two reservoirs is more than 2100 ft.

The oil composition in El Furrial Field changes rapidly with depth from conventional oil (28 °API) at the top of the formation to tar, at the base of the reservoir. The initial reservoir pressure was 11,258 psi at 13,800 feet subsea, indicating significant over- pressured conditions, at average reservoir temperature of approximately 300ºF. The porosity ranges of between8-15% and permeability between 60-1200 md.

Initially, the production mechanism was natural depletion under rock-fluids expansion. Secondary recovery processes were applied later, flank water injection in Naricual (1992) and then in Los Jabillos (1997). In 1998 crestal miscible gas injection started in Naricual

Background

A previous feasibility study revealed that WAG could increase recovery up to 60% (IOOIP) (Fig. 2). Thus, in order to better study and compare EOR processes, a new static and dynamic characterization was started in year 1999. The goal of this new project was to build a full field 3D numerical model

(El Furrial V9), able to simulate different kind of processes, such as WAG, miscible gas injection, dewatering, nitrogen injection, etc.

Preceeding the V9 model, "Naricual" and "Los Jabillos" formations were studied separately. Eight previous versions existed for reservoir models in Naricual and one previous model had been constructed for Los Jabillos. Those studies suported the pressent recovery process and pressure maintenance for the field, ie, crestal miscible gas injection and flank water injection.

Static Model

The static model represents one of the most significant changes of this new study, getting itself up to a greater degree of detail to diminish the geologic uncertainty. A better characterisation of the field heterogeneity was obtained through the construction of the new static representation supported by updated structural, stratigraphic, sedimentological and petrophysical models.

Structural Model

The actual structural model is based on the new 3D seismic interpretation. This seismic acquired in 1998, has an acreage of 370 Km2 and shows remarkable improvements in terms of quality and coverage with regards to the 1993 one which covered only 210 km2. (Fig. 3). This new seismic interpretation furnished a better structural definition for the flanks, and the northern thurst. Also, a better imaged was achieved for the "autoctono", and for primary and secundary faults (Fig. 4).

The new structural "full field" model points that El Furrial field is a 20 Km large ramp anticline, which axis is N70E trending, divided into three different areas each one characterised by its own structural style. The northern dips are 12-15 degrees while the southern flanks are steeper with 20 degrees in average. The top of the field is reached in its western part at –12,400 feet sub sea. An important normal faulting is evidenced either from wells or from seismic, these faults having between 50 to 300 feet throw. This intense faulting generates a high structural heterogeneity but does not represent a barrier for the fluid migrations according to the dynamic behaviour of the field.

Two transfer zones with strike slip faults limit the field to the West from Carito and to the East from Corozo.

Stratigraphic Model

The initial stratigraphic model was generated based on regional chronostratigraphic framework (third and fourth order sequences), where thirteen main markers are defined (maximum flooding surfaces and flooding surfaces). These markers which extend from Lower Miocene (top Upper Naricual M3 marker) to Intra Cretaceous (M15 marker) cover the whole sedimentary sequence involved in the hydrocarbons trap. With the purpose of having a better knowledge of the internal architecture of the field and of the main flow units, a refined description was performed. This refinement was based on biostratigraphic interpretations, sedimentological core analysis results and on log derived sequence stratigraphy. This lead to the identification of 46 local isochronous shaly markers, a few feet to a hundred feet thick, and assumed to represent flooding surfaces. Between these shale occurrences 47 sand sequences are identified, a few feet to 200 feet thick, and assumed to represent hydraulic units (Fig. 5). However, in the field, most of the vertical seals are affected by dense faulting, partial and total erosions, which allow total or partial communication between the different flow units.

Sedimentological Model

This first sedimentological model of El Furrial field was generated using 13692 ft. of conventional cores, and paleontological data from eight wells. This model includes 24 paleoenvironmental maps, wich were used to define principal depositional directions for geostadistical model. Lower and Upper Naricual members are divided into two main cycles. The first one starts with a general unconformity (intra Maastrichtian) and is represented by fluvial channel stacking deposits (Upper Maastrichtian in age). It is overlaid by distributary channels and littoral bar sediments from Paleocene-Eocene draped by a glauconitic condensed section, Lower Oligocene in age. The second cycle totally erodes the glauconitic section to the West, it is composed by channel and nearshore bar deposits with coal seams and paleo soils evidences, followed by distributary channels and littoral bars ending with marine offshore bars and shales dated Upper Oligocene to Lower Miocene. The thick Carapita shales, Lower to Middle Miocene, originate the general seal of the field.

Petrophysical Model

This new petrophysical model is based on the information from 13692 feet of cores and logs from the 164 perforated wells (Fig. 7), and allow discribing better the heterogeneity of the field.

Further to deterministic analysis of the rock properties (porosity and water saturation) special core analysis results allowed the characterisation of 6 rock types, according to pore throat sizes, which were after that correlated with log responses in each drilled well. Each one of these rock types is characterised by its own permeability law. Four are considered permeable (2 mega porous, 1 macro porous and 1 meso porous), one tight (micro porous) and one sealing (nano porous).

This rock type definition allows a better understanding of the reservoir behaviour and the ranking of sand units based on storage and flow capacities in order to optimise production and injection processes.

Fluid Model

A new model for fluid distribution was generated, on basis of production data and geochemical analyses.

The fluid distribution model includes a tar seal, which has been partially cored in well, to explain the water and oil distributions over the field. In the southernmost part of the field the column is represented by medium crude over heavy oil with an oil water contact at –15200 feet sub sea set on a tar seal. To the centre and to the north of the field no water has been evidenced at –17000 feet sub sea (Fig. 9). The Tar seal, supposed to represent the paleo oil water contact of the proto Furrial field, is shaped by post tectonic events in such a way that a hinge line has been created which isolates north from south aquifers. The so generated tar surface is irregular, and tectonically folded in agreement with the general structure. Communications within the oil column are evidenced by dynamic behaviours and injected tracers.

Among the whole fluid column thermodynamic variations as a result of the various pulses of oil generation and physical / chemical processes which occurred into the reservoir were identified. Biodegradation, gravitational segregation, evaporative fractionation are the most evident processes that have affected the composition of the initial crudes, originating the fluid distribution that is actually present in the field.

This new model broke with the paradigm of the official fluid model in which the accumulation is limited to the North sealing faults. This new vision for the fluid accumulation is one of the most important changes included in V9, inducing the existence of new reserves and possible extensions for the field, justifying in this way new opportunities for the future growth of El Furrial field.

The new fluid model has been confirmed by advanced drilling activity, over zones considereded before as having non economical interest. The new fluid interpretation is of interest, as it includes a new maximal thickness for tar in sand.

Geocellular Model

A geocellular model integrating the new structural interpretation, the chronostratigraphic and sedimentary frameworks together with the petrophysical model has been generated on a 3D simulator using a corner point geometry (Fig. 10).

In a first step generated the stratigraphic and structural grids were. At this point 70 principal faults were incorporated together with 11 stratigraphic units that correspond to 350 millions cells.

In a second step each stratigraphic unit was modelled independently according to sedimentary pattern in agreement with regional sedimentary configuration. The geostatistical simulation was performed using a pluri Gaussian interpolation with non-stationary Vertical Proportion Curve to better represent the sediments and property changes throughout the field. Various realisations were performed for each unit without any significant differences due to the high density of conditioning wells.

In a third step the results were upscaled into rock types and porosity. At this stage the model counts with 930 thousands cells (of which 500 thousands are active), 47 layers, 70 principal faults and 130 secondary faults.

Finally, the Tar surface was introduced into the model to limit vertically the accumulation, (reason why in the simulation model the cells below Tar are considered inactive).

Thermodynamic Model

The thermodynamic behaviour of the fluids in the El Furrial Field matchs with the classification of a Black Oil Reservoir, with strong compositional segregation. The saturation pressure varies from 4800 to 1800 psia and the oil density varies from 30 to 16 °API as shown in Fig 11. These changes in the thermodynamic properties throughout the fluid column were perfectly modelled in order to reduce the uncertainty on the forecasts of the Miscible Gas Injection currently carried out in the Naricual Superior Reservoir.

First of all, it was necessary to validate 50 PVT studies. As a result of the validation stage only 16 were considered both consistent and representative. The next step was to fit the 3 Parameter Peng-Robinson (PR) EOS for which were used 4 PVT analysis. The fitting was found grouping the components of the samples in 7 pseudocomponents and modifying the properties of the heavy fraction C20+. Then, fluid propertie tables versus depth for Black Oil simulations were generated, as well as a table of fluid compositions versus depth for Compositional Simulation. The fluid viscosity was modelled separately using the Lohrenz, Bray and Clack Correlation (LBC) and also changing the C20+ properties.

The quality of the EOS fitting was validated by modelling several laboratory experiments. Both swelling tests and slimtube experiments were matched with enough accuracy. The match of experimental data was carried out using 1-D, 400 Grid Block Cells, Compositional Simulation Model. Also, this model was used to calibrate Todd-Longstaff coefficient (ω) so as to run faster black oil simulations and reproduce the miscibility effects.

Rock-Fluid Model

According to the results of special core analysis, the condition of wettability observed in the reservoirs of El Furrial Field is variable. Good quality rock is strongly oil wet, and the poorer quality rock presents intermediate wet system. The irreducible water saturation and the oil saturation after water and gas flooding also depends strongly on rock quality. Furthermore, strong hysteresis effects on the water permeability curve appear to be present by the presence of trapped water saturation values up to 35%.

The modelling of the capilar pressures and relative permeabilities under these conditions was carried out using the methodology proposed by Skjæveland et al[1]and Kjosavik et al[2], respectively. Only aged and restored samples with reservoir fluid were used to calibrate the KRPC model. A set of curves was generated which covers the whole range of rock types found in the reservoirs as shown in (Fig. 12).

History Match

The model has been history matched against 17 years of historical data of which 11 years included flank water injection and 5 years of miscible crestal gas injection. The historical period ends in September 2003. Production data was updated during the History Match process. The general methodology applied includes:

Global Energy History Match: Communication with Carito neighbor field was investigated and global rock compressibility was slightly modified. No porosity or absolute permeability modifications had to be performed for Naricual. In this way, static model was validated to some extent.

Fault transmissibility modifications along major faults (more than 60): in order to match water production in some wells, fault transmisibility was modify.

PLT Matching Process: Well profiles were adjusted against historical PLT-data (PI modifications) when available. This correction was very important, as wells produce from several sands with different potential.

Kr-Pc Model modifications: Original KR-PC model was issued from SCAL over cores extracted with oil based mud. Therefore, wettability on the model could be over estimated. New Kr-Pc data was generated, allowing reproducing water cut profiles in many areas of the field. Also, set of pseudo curves was generated in order to minimize grid block size effect in some zones.

Besides, extensive transmissibility barriers were needed to separate Cretaceous from Naricual, as they shown very different pressure vs. time profiles. This barrier was later confirmed by a new petrophysical interpretation, which discovered a low permeability layer on the top of Cretaceous.

As a final modification before the prediction runs the productivity index of each well has been modified to match the measured bottom hole pressures.

At the end of the History Match Process, Furrial model was close enough to reality to allow it to use for global predictions (See Fig. 13, Fig.14 y Fig. 15).

Determination of New Well Locations

In order to determine the most prospective zones in the field, an “Opportunity Index” (OI) was created. This index includes roughly areal uncertainties of the model, according to difficulties encountered during History Match. The index, calculated for the present state of the field, considers the residual mobil oil distribution, and the rock properties. The OI is composed by four sub-index, and is calculated by means of the following formula:

$$OI = \sqrt[4]{Iom\ Ivp\ Icf\ Iu}$$

With:

OI = Opportunity Index.
Iom = Mobil Oil Index.
Ivp = Oil Volume Index.
Icf = Flow Capacity Index.
Iu = Uncertainty Index.

Mobil Oil Index (Iom): Considers the portion of remaining oil that will be able to flow towards wells. It is defined after the following formula, applied on a reservoir basis:

$$Ioil\quad mov(CELDAS\quad I,J) = \frac{\sum_n (So_n - Sorw_n)\times VP_n}{\sum_n VP_n}$$

With:

I,J : Coordinates for the cell in the grid.
Son : Present oil saturation in cells of the layer “n”, location I,J.
Sorwn : Residual Oil Saturation, after water sweeping (only water swept was considered), for the layer “n”.
VPn: Pore Volume of the cell.

Oil Volume Index (Ivp): Considers exclusively the remanent oil distribution, regardless it will flow or not. In this way, because of Iom and Ivp, oil volume is weighted twice in the global OI index. This Index was added on a reservoir basis.

Flow Capacity Index (Icf): This Index is issued from an armonic average of flow capacity of the “n” cells belonging to each reservoir.

Uncertainty Index: Varies from 0 to 1. Provides a rough approximation for areal uncertainty of the forecast obtained with the model. It has been estimated during the History Match process, according to difficulties encountered on each zone.

The resulting OI is indeed a subjective value, as many other definitions could be proposed in order to quantify present prospectively distribution in the field. Even though the correlation between this particular OI, ultimate well oil recovery, and initial well potential was confirmed, OI was only used as a first approach in order to guide new location definition. All new location thus defined were latter compared on a purely forecast results basis. See Fig. 16, Fig. 17 y Fig. 18.

Forecasts

El Furrial full field model V9, once history matched, allowed to evaluate the effect of different production scenarios in the future performance of the field. Several alternatives to pressure maintenance have been compared and ranked from a technical and economical point of view. Studied scenarios include water injection on the flanks and crestal miscible gas injection, dewatering, and different implementation for WAG injection processes. Each scenario was conceived in agreement with a special drilling plan, which varies depending on the pressure maintenance process. Nearly 70 new wells were defined over the zones that showed to be more prospective.

The model also allowed to study the effect of a reduction in well spacing (set in 600m by state regulations). Results showed that a reduction in spacing increases economical value, but doesn't affects ultimate recovery, which seems to be sensible to the nature of recovery process only.

As simulation forecasts considered pressure losses in well completions, it was possible to quantify the benefit from the use of artificial gas lift in wells. Some other artificial lift methods can be analysed in the future, providing adapted vertical lift performance curves are generated.

Only the black oil PVT model was used so far. However, a compositional PVT model is ready to be used if required. The model can also support asphaltene precipitation studies.

The model is used on a regular basis for WorkOver, transient pressure test designs, and new wells production forecasts.

Results

New Well Proposal

In order to sustain the future development of the field, 70 new well proposals were defined based on simulation results. Among those 70 new wells there are many production wells, some advanced wells over non-proved zones, and new injectors to guarantee pressure maintenance.

Exploitation Scenario Evaluation

Several Exploitation Scenario were evaluated, including EOR process such as WAG, Dewatering by crestal gas injection, pure flank water injection, etc, in order to define a new exploitation strategy for the field (Fig. 19). Simulation results were used in a special integrated project (MIA or "integrated asset modelling"). Within MIA project, a decision matrix was generated considering several economic parameters, risk and uncertainties.

New Production Opportunities Identification

The new fluid model considered in V9 allowed identifying new producing zones, with expectations to increase IOOIP in 1,3 MMMBls. Thus, several zones considered before as field limits were added to the pool. New drilling activity was then programed over these new zones, in order to better estimate potential and look for new limits. Moreover, one of the wells drilled in the northern zone found a new 600ft oil column below the official inferior limit of the structure. This new prospect was confirmed with formation fluid samples, which indicated light oil ranging from 25,7 to 27,8 API.

Coupled Reservoir/Production Facilities Simulation

The V9 reservoir model was successfully coupled with a production facilities simulator, which considered the entire collecting network of 130 active completions, connected with more than 500 Kms of production pipes. The production network sends oil, gas and water production to three different pressure levels. The coupled model is one of the biggest in the world.

These applications were oriented to support El Furrial Oil Field production strategy by planning medium term (1-10 years) production forecasting and allocation of additional surface facilities. (Fig. 21)

Some advantages of this integrated model are the fact of considering the effect of several hydrocarbon reservoirs sharing the same surface facilities and the pressure interaction between these reservoirs and constrained surface network. Conventional reservoir simulation generally ignores these effects. The integration procedure and the coupling location used allows dynamic changes in the surface network model (well chokes, equipment schedule, flow distribution in the network) to assure an optimized production strategy. The integrated simulation shows realistic result and provides a production strategy to maximize hydrocarbon recovery and a methodology to evaluate production enhancement projects. By using these applications of integrated reservoir and surface network simulation, the reservoir management is envisaged to improve significantly in El Furrial Oil Field.

Mecanistic Studies for WAG Process

The model was also used to design a pilot WAG test. A zone of the full field model was extracted and refined, and then used to simulate the pilot WAG test under different conditions. This study allowed determining optimized frequencies for alternated injection, fluid volumes, and other parameters needed to optimize the pilot test.

Conclusions

1.- New seismisc interpretation improved definition of the complex structure that takes place on the field.

2.- A better heterogeneity characterization was obtained from the new petrophysical model, which considers differents rock types.

3.- A unique EOS PVT model was built and calibrated, describing global fluid behavior in a more consistent way.

4.- The revised fluid model broke up with the concept of “horizontal tar-mat”, giving in this way a more realistic distribution of fluids. By extrapolation of the fluid model, new prospectives zones were inferred, and then confirmed.

5.- The updated rock-fluid model allows studying non-conventional EOR processes such as WAG.

6.- The use of OI (Opportunity Index), based on the modelized present state for the field, helped to define 70 new well locations.

7.- V9 model gave a new image of the field, showing an IOOIP increment of 1.3 MMMBls.

8.- Based on V9 model, a detailed Secondary Recovery Study was conducted, and a better explotaition strategy was defined.

References

[1]Skjæveland, S.M., Siqveland, L.M., Kjosavik, A., Hammervold Thomas, W.L., and Virnosky, G: “ Capillary Pressure Correlation for Mixed-Wet Reservoirs” *SPE Reservoir Eval & Eng*., **3** (1), pp. 60-67, February 2000

[2]Kjosavik, A, Ringen, J.K. and, Skjæveland, S.M.:”Relative Permeability Correlation for Mixed-Wet Reservoirs”, *SPE 59314*, 2000 SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, 3–5 April 2000.

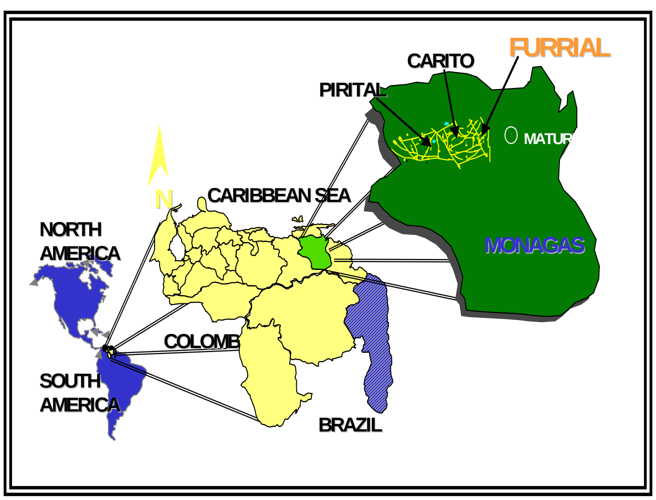

Fig. 1.- El Furrial Field Location

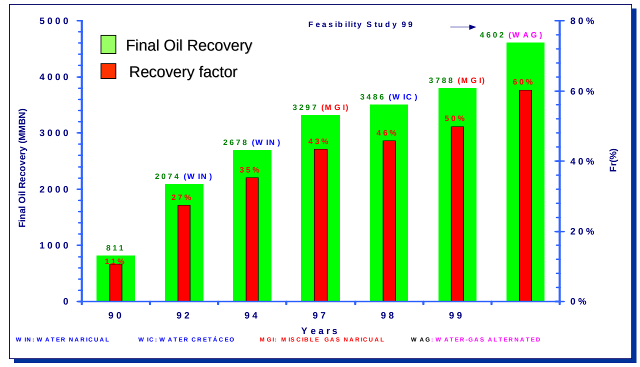

Fig. 2.- **Feasibility Study El Furrial Field**

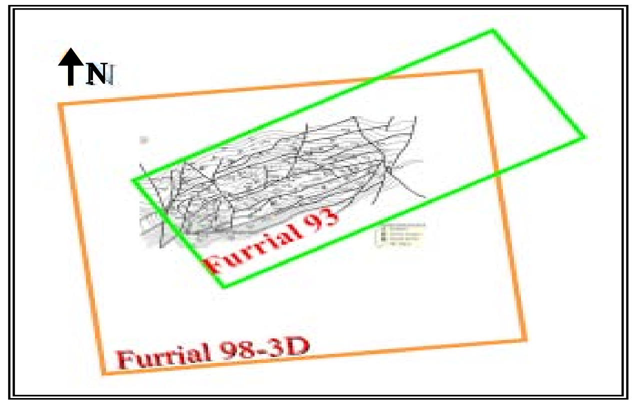

Fig.3.- Area Seismic El Furrial Field

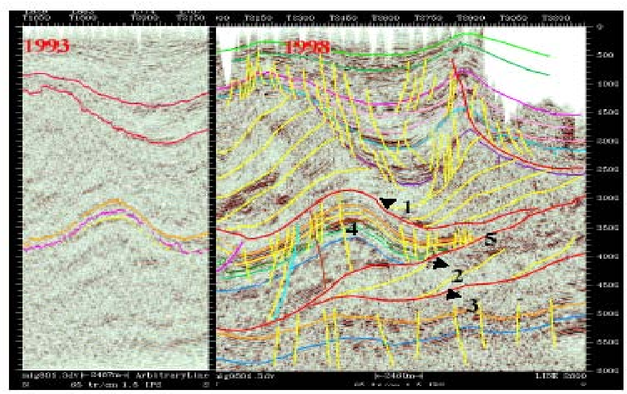

Fig.4.- New Seismic Interpretacion.

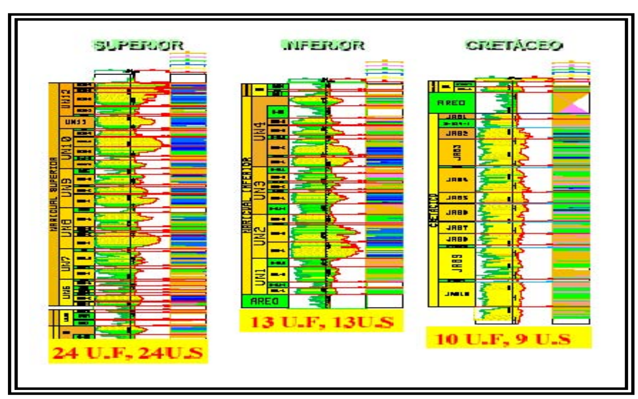

Fig. 5.- Stratigraphic Model

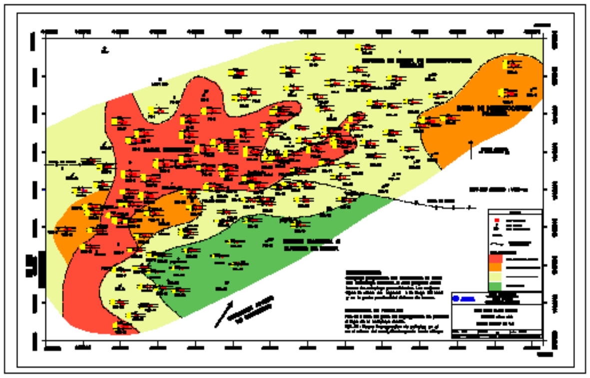

Fig. 6.- Sedimentological Model

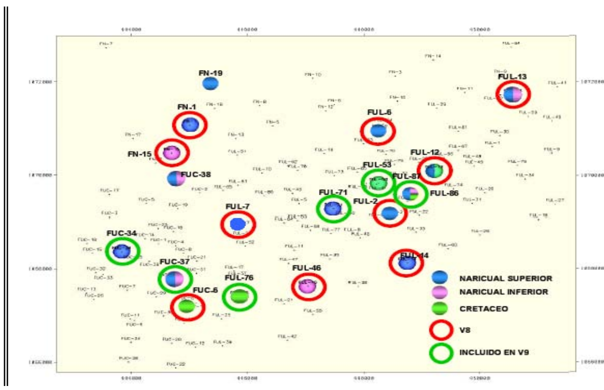

Fig. 7.- Core Distribucion El Furrial Field

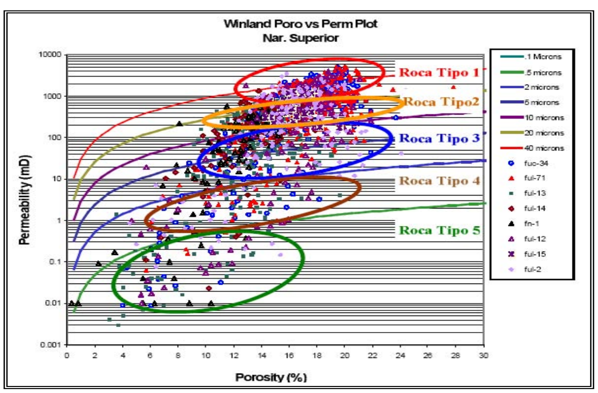

Fig. 8.- Petrophysical Model

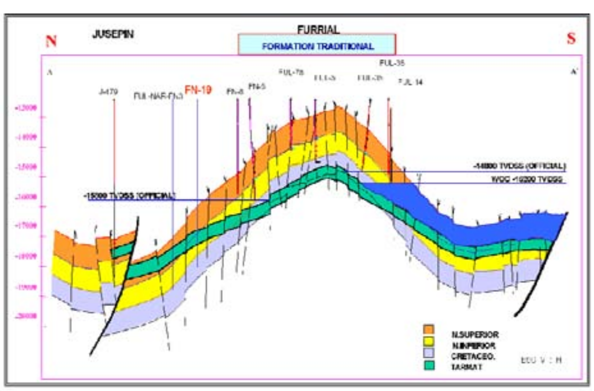

Fig. 9.- New Fluid Model

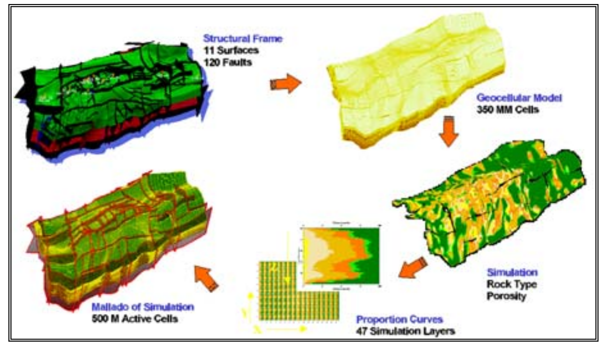

Fig. 10.- Geocellular Model

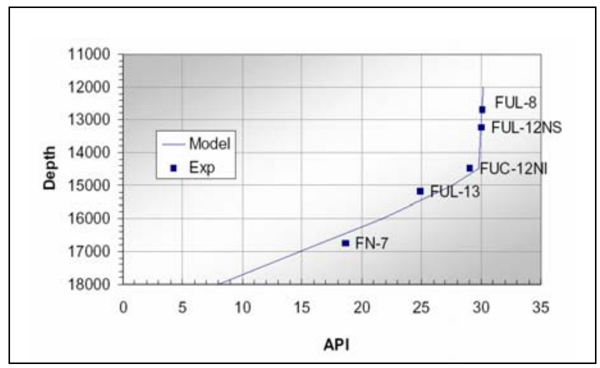

Fig. 11.- Oil Densities versus Depth

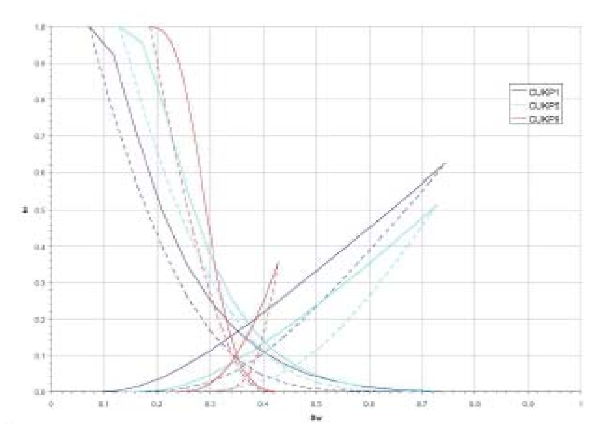

Fig. 12.- Rock Type Model

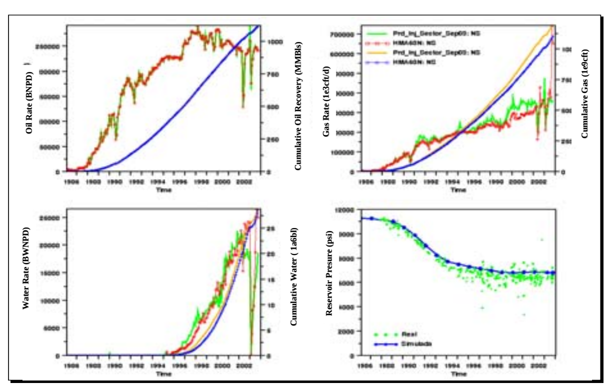

Fig. 13.- History Match Reservoir Naricual Superior

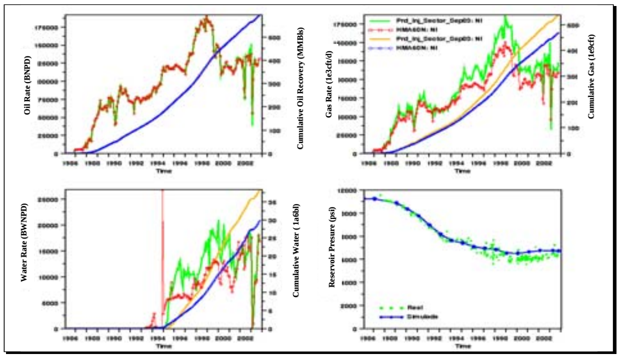

Fig. 14.- History Match Reservoir Naricual Inferior

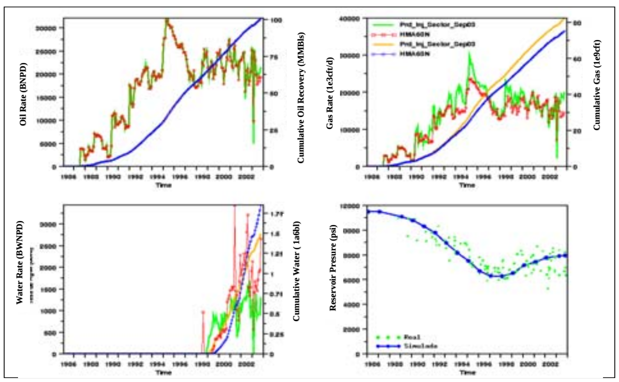

Fig. 15.- History Match Reservoir Reservoir Cretáceo

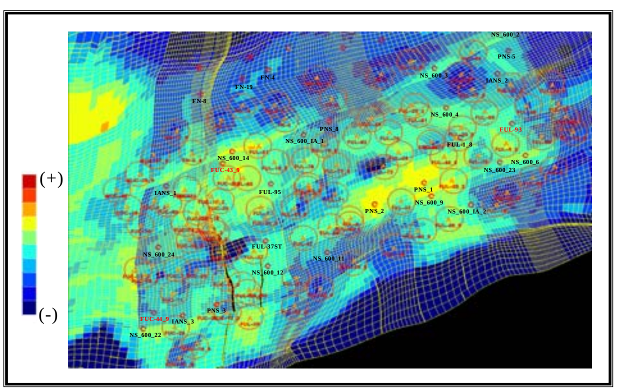

Fig. 16.- New Well Locations Reservoir Naricual Superior

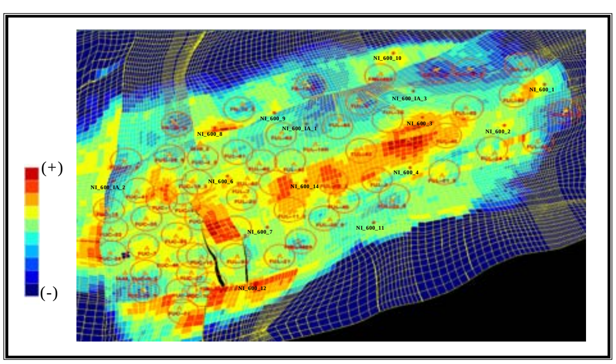

Fig. 17.- New Well Locations Reservoir Naricual Inferior.

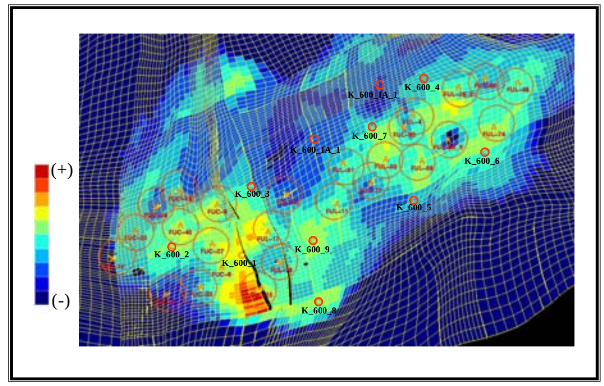

Fig. 18.- New Well Locations Reservoir Cretáceo

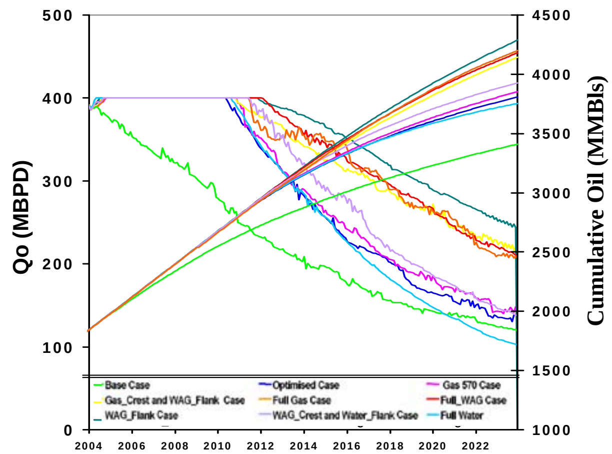

Fig. 19.- Explotation Scenari Evaluation

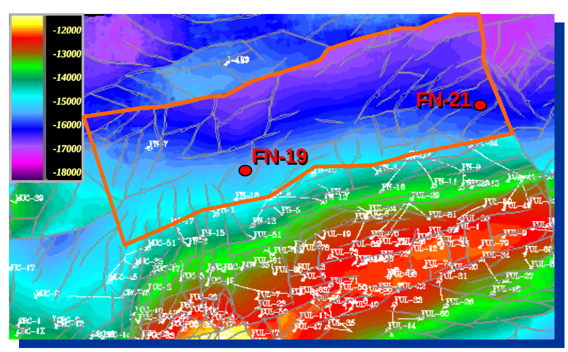

Fig. 20.- New Producing Zones El Furrial Field

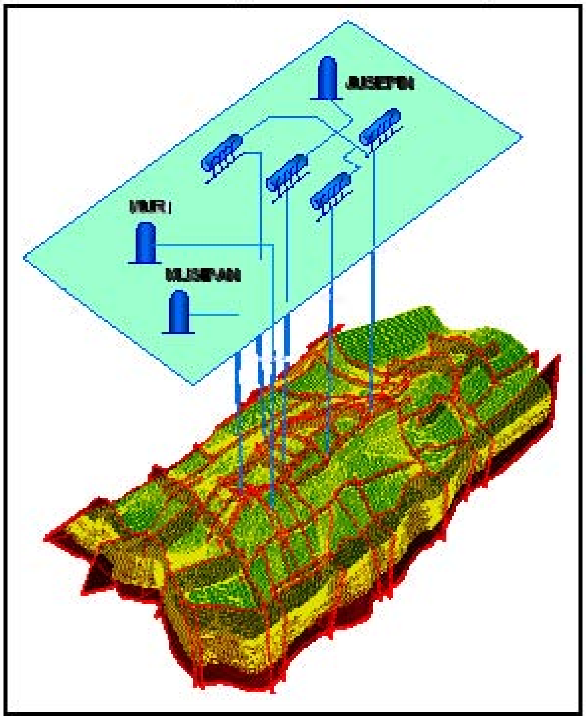

Fig. 21.- Coupled Reservoir/Production Facilities Simulation .

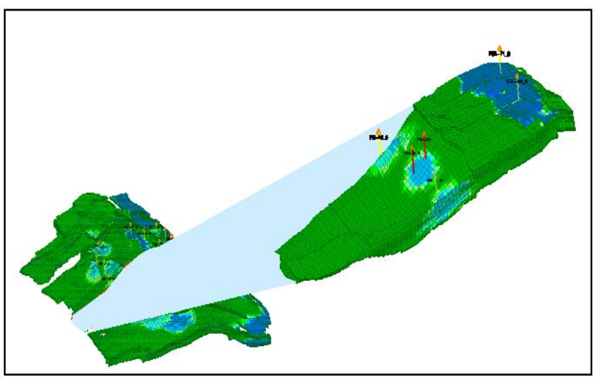

Fig. 22.- Pilot WAG