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Nakhla Oil Field, Concession 97, Libya
Development Strategy and Improved Oil Recovery

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حقل النخلة النفطي بعقد الامتياز 97 بليبيا:
إستراتيجية التطوير وتحسين المسترد الإضافي

طوماس فرانزن

حقل النخلة النفطي عبارة عن كتلة متصدعة مائلة باتجاه شمال غرب-جنوب شرق يدار من قبل شركة فينترسال ليبيا.
ترسبت الصخور المنتجة بهذا الحقل – إبان العصر الكريتاسي في بيئة نهرية ويتكون الجزأين السفلي والعلوي من هذا التكوين من صخور رملية تفصلهما عند الوسط طبقات من صخور الطفلة.
ويقتصر تواجد النفط الخام بالطبقة العلوية من هذا التكوين وبشكل عام فإن المكمن غير متجانس ومجزّء إلى سحنات.
يجري استخراج النفط من حقل النخلة منذ 28 مايو 1995 حيث أنتج حوالي 22 مليون برميل من النفط الخام حتى تاريخ 2002/12/31، وبناء على طريقة محاكاة المكمن يقدر المسترد الأقصى في الوقت الحالي بحوالي 6.5% (يوليو 2002)، كما تم استخدام هذه الطريقة في التنبؤ بالمناطق ضئيلة الإنتاج والتخطيط للحفر بين الآبار المنتجة.
لقد تم حفر ثمانية آبار عمودية وبئر أفقي وبالنظر إلى صعوبة التنبؤ بالصخور البركانية فقد كانت ثلاثة آبار منها جافة، وعلى أية حال فإن المرحلة التالية لتطوير حقل النخلة ستتم بحفر ستة آبار إضافية أخرى. وعندما يتم هذا التطوير فإن الحد الأقصى للاسترداد الإضافي سيصل إلى حوالي 114 مليون برميل (12.3 الاسترداد النهائي). وكذلك تم التخطيط لمزيد من التطوير ولكن يستلزم الأمر تطبيق ما قبل SDM والتفسير السيزمي لإعادة تقييم نموذج المكمن الديناميكي والجيولوجي.
تناقش هذه الورقة إستراتيجية تطوير الاسترداد الإضافي المتبعة حاليا والمتوقعة في المستقبل المنظور مثل:

- دراسة تحسين المسترد النفطي (صيانة الضغط).
- دراسة الاسترداد الإضافي (مثل حقن الغاز).

كما تم عرض النتائج الأولية للدراسات الجارية.

Abstract: *This paper presents the development strategy and the improved oil recovery potential of the Nakhla field. The Nakhla oil field is located in Concession 97 (G.S.P.L.A.J.) and is producing from the heterogeneous and compartmentalized Upper Sarir Sandstone since June 1995. Total production of the existing eight (8) vertical wells and one (1) horizontal well is approx. 22 MMSTB as of year end 2002. Seven vertical wells are hydraulic fractured and three wells are dry holes due to volcanics or technical problems.*

Within the next development phase (II) six (6) additional producers are planned. Based on the good experience all new wells will be drilled vertically and post hydraulic fractured. Updated static and dynamic simulation models have been used to optimize the development concept. Through natural depletion ultimate recovery

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estimates currently stand at 12.0% or 112 MMSTB.

Further development (Phase III) is planned, but ongoing PreSDM and seismic interpretation has to be implemented to re-evaluate the geological and dynamic reservoir model. Ultimate recovery including Phase III estimates stand at 152 MMSTB or 16.3% of oil initially in place (OIIP).

To increase the ultimate recovery even further the 'Improved Oil Recovery (IOR)' potential is currently under investigation. Available input data was reviewed and new SCAL and PVT including special IOR/EOR data was requested. Laboratory results will be available by end of year 2003 and will be implemented into a new compositional reservoir simulation. In the meantime a preliminary analytical screening was performed to identify viable IOR/EOR techniques and to estimate 'Performance Indicators' of the West and East field regions.

Estimated 'Performance Indicators' vary between 13% - 19% for immiscible injection gas and 17% - 19% in case of miscible injection gas. In addition to improving oil recovery, the re-injection of produced gas would avoid gas flaring and confirm Wintershall's policy to protect the environment. Water flooding is predicted to give good recoveries, too. However, low permeabilities may prevent or restrict injectivity into the reservoir. Further investigations are necessary and will be performed on a full-field compositional model.

INTRODUCTION

The Nakhla oil field is situated in the south-eastern part of the Sirt Basin in Concession 97, (Fig. 1). The field is a NW-SE fault bounded horst structure operated by Wintershall Libya.

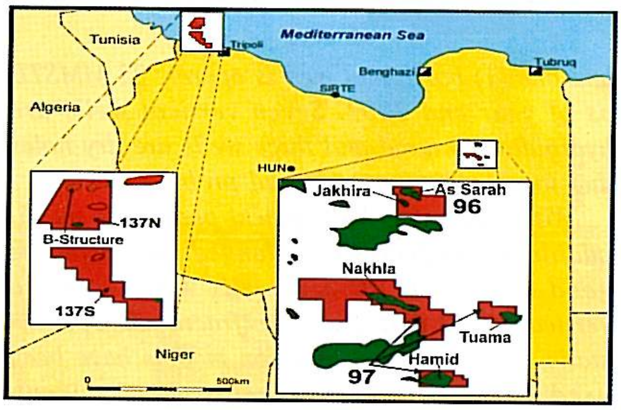

Fig. 1. Concession overview of Nakhla oilfield.

The field's reservoir is a Sarir Sandstone of the Lower Cretaceous age consisting of three subdivisions. A lower Sarir Sandstone is covered by The Middle Shale section which is overlain by The Upper Sarir Sandstone. The individual thickness of all three members vary throughout the trough, and only the upper sandstone is oil bearing.

The current knowledge of the Nakhla oil field proved the heterogeneity of the Sarir Sandstone and in some areas volcanics have replaced the sandstone entirely. The existing wells have penetrated regions of poor reservoir quality in the west and moderate to good in the east. The seismic coverage indicates a complex tectonics.

Since June 1995 Nakhla is on stream and has produced approx. 22 MMSTB from eight vertical wells and one horizontal well till year end 2002. Based on natural depletion ultimate recovery estimates currently stand at 62.0 MMSTB; i.e. 6.6% of OIIP (Status: Dec. 2002).

Within the field development so far (Phase I) seven of the eight vertical wells are hydraulic fractured. The horizontal well is an open-hole completion.

Currently, the Nakhla oil field can be classified as immature and further development of the structure is planned within development phases II and III.

Objectives of this paper are to present briefly the actual field status and the development strategy followed so far to accelerate the oil recovery by natural depletion. The development concept of the planned phase II and phase III will be presented.

Further this paper discusses oil recovery improvements scheduled or currently under investigation on:

- Improved Oil Recovery
  and
- Enhanced Oil Recovery.

Preliminary results from a first look analytical screening will show viable IOR/EOR techniques and how a 'Performance Indicator Screening' has been performed to estimate recovery factors for the West and East regions of the Nakhla field.

CURRENT NAKHLA DEVELOPMENT

The current Nakhla Development is based on a static/geological model which incorporates structural, facies and petrophysical evaluations. The structure has been shaped by various tectonic events and can be described as an extensional north-tilted horst block in the Hameimat Trough (Fig. 2).

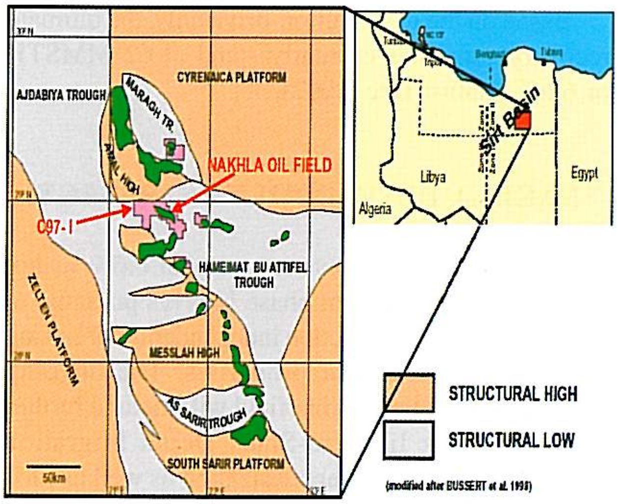

Fig. 2. Structural setting of Nakhla oilfield.

In accordance to Robertson Research studies[1] and using GR-curves the facies breakdown was evaluated. Channels have been assigned below 22 API, sandflat facies type between 22 - 45 API and above 45 API as floodplain facies type (Figs. 3 and 4). The following volumetric ratios have been evaluated:

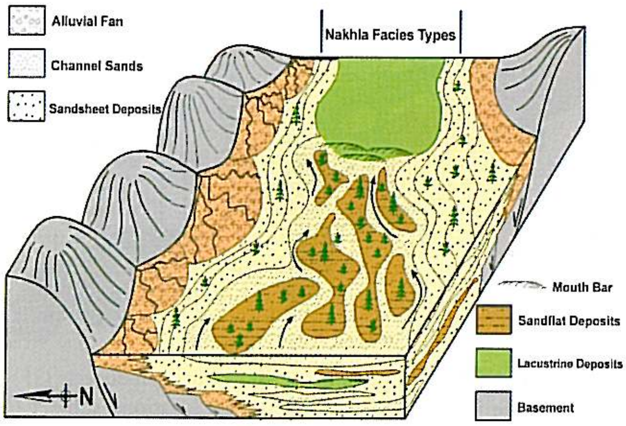

Fig. 3. Depositional model of Sarir Sandstone.

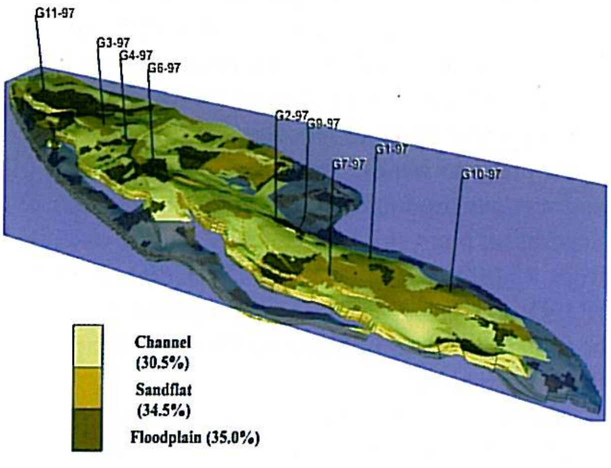

Fig. 4. Facies model of Sarir Sandstone.

Channel	30.5%
Sandflat	34.5%
Floodplain	35.0%

The petrophysical model is based on well results and on log data. Interpretations confirmed poor to relative good reservoir properties, *e.g.* permeabilities in the western region vary between 0.25 – 10 md and in the east region between 5 – 12 md. Overall, the reservoir is very heterogeneous and compartmentalized.

Based on available G and G data including a 3D seismic interpretation update a new integrated geological model has been created in May-June 2002 (Fig. 5). The high resolution of the static model with 3.75 million grid cells (250 columns * 150 rows * 150 layers) honours the complex tectonic framework and the heterogeneity in horizontal and vertical direction (Figs. 5 and 6).

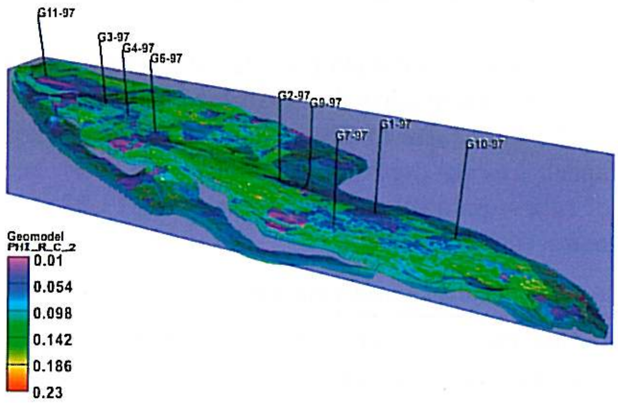

Fig. 5. Porosity distribution of Sarir Sandstone.

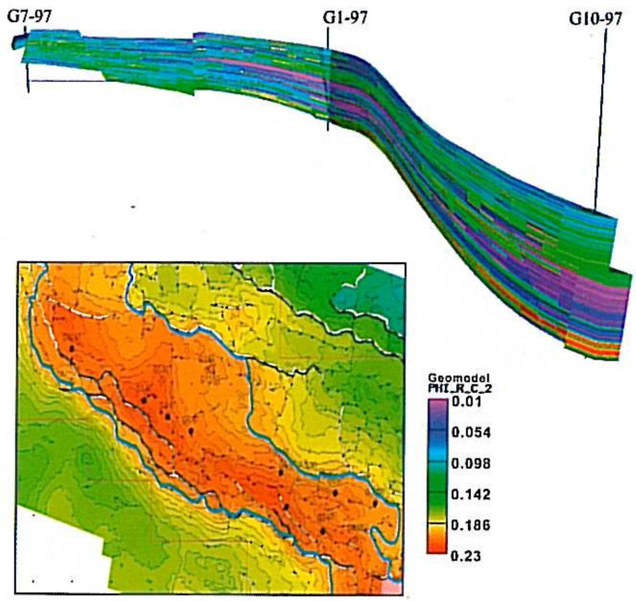

Fig. 6. Fence diagram along G7-, G1- and G10-97 showing blocked well data and possible porosity distribution.

Further volcanics spots had to be considered in the model due to drilling results of wells G5-97, G12-97 and G13-97. A conceptual assumption volcanic occurrence is presented in Figure 7, but volcanic sills and dykes are often below seismic resolution.

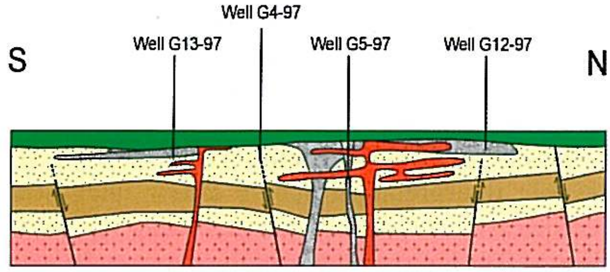

Fig. 7. Volcanic sills and dykes (conceptual).

Finally, the geological model and the evaluated porosity distribution were upscaled to 250*150*18 layers to be used in the dynamic reservoir simulation model.

A full-field simulation model was performed in July 2002 and initialized on available PVT[2] and core/SCAL data (Table 1). The geological model was not updated by the dry hole results of well G13-97, but of course pre-evaluated production of G13-97 was removed (Fig. 8).

Table 1. Simulation model parameters, post G13-97.

Grid size:	250 x 150 x 18 (T/A 675/216 M
PVT model:	cells)
k/Pc model:	PERA, March, 2000
2000/200	Wintershall Lab and ETL,
Prod. start:	June 29th, 1995
Producers, vert.:	G1, G2, G3, G4, G6, G7, G10, G11
Producers, hor.:	G9
dry holes	G5, G8, G12, G13
hydr. fracs:	G1, G3, G4, G6, G7, G11

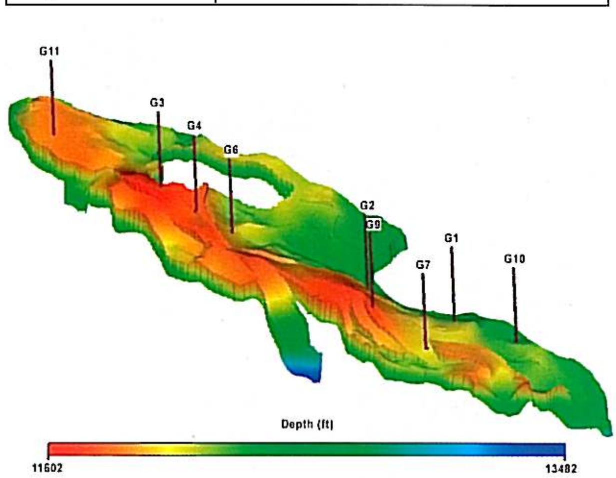

Fig. 8. Simulation model – phase I, existing producers: G1-G11.

Based on the gas-solution-drive only, the ultimate recovery estimates currently stand at 62 MMSTB or 6.6% (status: Dec. 2002).

NAKHLA DEVELOPMENT STRATEGY

The estimated ultimate recovery of 6.6% within the Nakhla development phase I leaves potential to increasing the oil production independently of having good or poor reservoir properties. The ongoing development of the Nakhla field will include further appraisal work like Pre-Stack Depth Migration (PSDM), Reservoir Characterization as well as FMI Interpretation.

Within the phase II development, the drilling of six (6) additional producers is planned in the proven area of the field (Fig. 9). Established on the geological model as of July 2002, plus considering a sealing fault to the southern compartment, the existing reservoir simulation model was modified to predict the field performance.

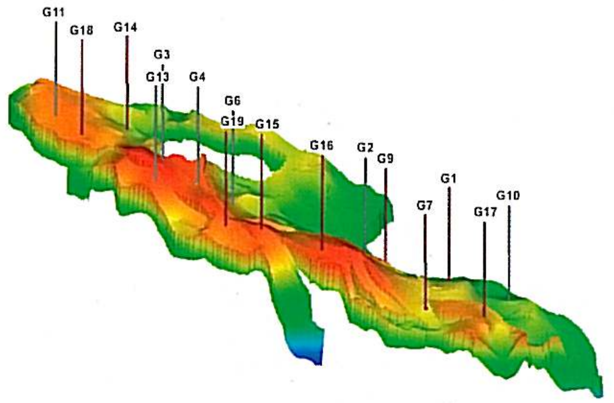

Fig. 9. Simulation model – phase II, existing producers: G1 – G11, phase II wells: G14 – G19 (well locations subject to revision).

The simulated reservoir pressure after a production period of almost 33 years is shown in Figure 10. Furthermore the final oil saturation is presented in Figure 11. Cumulative production is predicted at 111.9 MMSTB and ultimate recovery stands at 12.0%.

In order to handle the projected increase of oil and wet gas production the current Nakhla Gas Oil Separation plant (GOSP) capacity will be extended from 15,000 BOPD and 15 MMSCF/D to 30,000 BOPD and 40 MMSCF/D. The produced gas will be fully utilized to eliminate gas flaring and to protect the environment.

To increase the Nakhla production, further additional development well locations have been identified in the reservoir model as of July 2002.

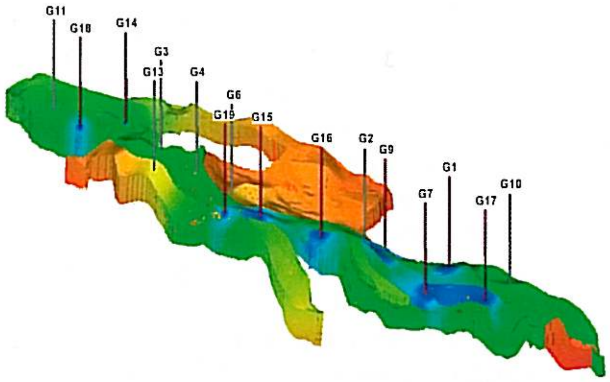

Fig. 10. Final pressure map – phase II, existing producers: G1 – G11, phase II wells: G14 – G19 (well locations subject to revision).

Based on economic evaluations, additional seven (7) development wells could be drilled. Of course, the ongoing field development and studies will provide further feedback to confirm the proposed phase III well locations, but the proposed well spacing would leave opportunities for further wells.

Seven (7) additional development wells of Nakhla phase III have been investigated using the dynamic reservoir simulation of July 2002. Considering the dry hole results of wells G5-97, G12-97 and G13-97 an incremental production of 40.5 MMSTB can be produced within the Nakhla development phase III.

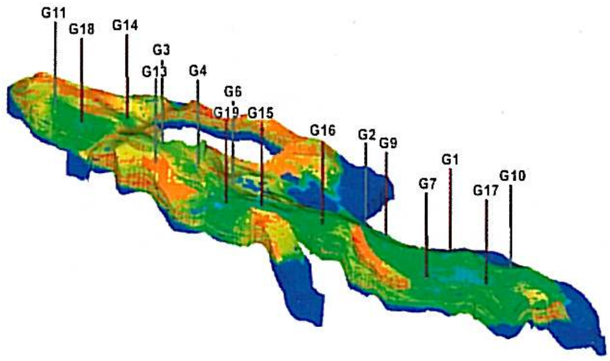

Fig. 11. Final oil saturation map – phase II, existing producers: G1 – G11, phase II wells: G14 – G19 (well locations subject to revision).

IMPROVED OIL RECOVERY

To avoid flaring of produced gas and to maintain reservoir pressure in the Nakhla oil field an 'Improved Oil Recovery (IOR)' feasibility study was performed in year 2000[3]. The scope of investigation was the western region with relatively good reservoir properties.

In general, the feasibility study proved an increased oil recovery by gas injection, but due to missing lab experiments some uncertainties on major input data are still existing. Therefore, the following recommendations were made:

- develop a new geological model.
- verify the injection gas comp.
- perform PVT laboratory experiments, including minimum miscibility pressure.
- update relative permeabilities.
- re-evaluate capillary pressure relationships.

Currently, all recommended studies are in progress and will be compiled in a new full-field reservoir simulation compositional model. However, in the meantime, analytical screening was performed to identify viable IOR/EOR processes and to estimate 'Performance Indicators' of the West and East Nakhla regions.

Performance Indicators

Developed by ECL Technology (formerly Subsurface Engineering Unit of AEA Technology) 'Performance Indicators'[4] is a preliminary screening tool based on analytical models to estimate the balance of viscous or gravity forces, sweep efficiencies *etc.* Parallel sensitivity runs can be performed to assess the impact of uncertainty on the flow mechanism and the viability of each IOR/EOR process.

A reservoir study on 'Performance Indicators' provides a qualitative understanding of expected displacements for single IOR/EOR processes and allows the elimination of unviable techniques in the case of a particular field.

Analytical Models

Two analytical models have been created based on log porosities from well G3-97 to represent the western region and well G7-97 for the eastern region of the Nakhla field. Permeability distributions are generated from evaluated laboratory porosity/ permeability correlations (Fig. 12). Accordingly to the Ö/k correlations, high permeability streaks have been included in the analytical model. Unfortunately, the model assumes connectivity of these streaks between wells and does not present the heterogeneity of the Nakhla geology.

IOR/EOR CASE STUDIES

Reference to the estimated 'Performance Indicators' is the Nakhla development phase II as

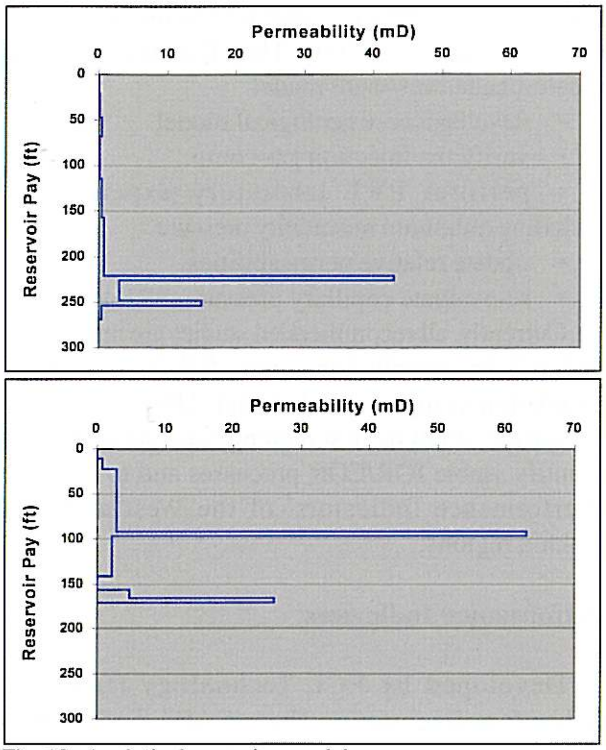

Fig. 12. Analytical screening models.

currently the most likely case (Table 2). The starting conditions used for the IOR/EOR screening and for all recovery factor calculations include: assuming an IOR/EOR start in the year 2006, approximately 29 MMSTB to be produced until year 2005, in addition to reducing the OOIP from 933 MMSTB to 904 MMSTB.

Table 2. Nakla C97/1 - development strategy and IOR/EOR case studies.

IOR/EOR	Oil recovery	
Start in 2006	West	East
Depletion	12.0 %	
Lean gas	13.3%	19.1%
Separator gas	13.3%	19.1%
Enriched gas	17.6%	25.2%
Waterflood	14.0%	14.6%
CO_2	No source	No source
Nitrogen	15.6%	22.4%

Gas Injection

Hydrocarbon gas injection was investigated in a pattern flood mode, because of the complex field compartmentalization. Three different gas compositions were used to consider miscible and immiscible conditions:

- Separator gas
- Lean hydrocarbon gas
- Enriched hydrocarbon gas.

In general, the low vertical permeability caused by claystone layers or lenses mean that gas can segregate slowly in the reservoir. This can be beneficial for gas injection and further claystone layers are probably not continuous between wells and may provide a tourtous route for the gas to move upwards. This improves the gas sweep. However, the areal heterogeneity cannot be adequately modelled using an analytical model.

In case of re-injection of 'Lean gas' (Table 2) the secondary recovery is predicted as 13.3% in the west and 19.1% in the eastern field region. The same results have been estimated for 'Separator Gas Injection', because of unchanged immiscible conditions (Table 2). To get a miscible flood a 10%- 15% NGL enrichment is required and recoveries by 'Enriched Hydrocarbon Gas' increase to 17.6% and 25.2% for west and east regions respectively (Table 2).

Water Flooding

A viscous dominated pattern water flood was performed to predict secondary recovery by pressure maintenance. The analytical model assumes good connectivity and no lateral heterogeneity between wells. The model, therefore, will predict no unswept reservoir regions and the actual sweep efficiency will be over-predicted. A risk factor has been introduced to compensate for the analytical model disadvantages.

The risked water flood secondary recovery is predicted at 14.0% and 14.5% for west and east regions respectively (Table 2). In addition the analytical method does not assess any injectivity issues, which would prohibit any water flooding in the first place.

CO_2 Flooding

Technically CO_2 flooding is an attractive EOR process, because it is naturally miscible with reservoir fluids. Enhanced recovery factors in the range of enriched hydrocarbon gas injection has been predicted. However, there is no source of CO_2 known in the vicinity of the field (Table 2).

Nitrogen Flooding

Nitrogen has to be generated in the field which will have an additional impact on economics. However, in the analytical study, the 'Minimum Miscible Pressure (MMP)' for the nitrogen case has been predicted to be lower than the MMP of hydrocarbon gas.

Based on a partial miscible flood the enhanced recovery is estimated at 15.6% and 22.4% for west and east regions respectively (Table 2).

Chemical Processes

The Nakhla reservoir temperature of 288°F would be too high for a Xanthan polymer to be stable. Further, the injectivity into the low permeability reservoir would be a problem.

Surfactant without a co-deployed polymer does not have a sufficient natural viscosity to provide a stable flood and will not be an option.

UNCERTAINTIES

To prove the quality of the analytical models major input parameters ranges have been used to examine the impact of uncertainties (Table 3).

The results of this uncertainty study shows no effects on the water flood efficiencies as the flood is viscous dominated.

Table 3. Uncertainty parameters.

Minimum	Minimum	Most likely	Maximum
Kv/Kh multiplier	0.1	1.0	10
Production rate @ west [BOPD]	300	500	800
Production rate @ east [BOPD]	300	1.500	2.700
Reservoir dip angle (deg.)	5.0	7.0	10
Well drainage area (width/length)	0.5	1.0	2.0
Reservoir pressure (psia)	3.000	4.200	4.500

The pattern gas flood is evaluated to be stable, too, but the uncertainties do affect the gas segregation in both field regions and reduce the vertical sweep in the west region of Nakhla.

Assuming higher permeabilities and formation net pay as represented around well G3-97 an additional sensitivity run was conducted. The results show slightly higher recovery factors of 14.1% in case of water flooding and 14.5% for hydrocarbon gas injection.

CONCLUSIONS

The Sarir Sandstone in the Nakhla oil field is very heterogeneous, tectonically complex, and the current development has proved regions of poor as well as relatively good reservoir qualities. In addition some sandstone areas have been completely replaced by volcanics.

Since production start mid 1995 till year end 2002 cumulative 22 MMSTB have been produced from eight (hydr fractured) vertical wells and one horizontal. The current ultimate recovery estimates stand at 6.6%. Further development requires a fully integrated approach of a multi-disciplinary team to manage geological and engineering uncertainties.

The results of G and G and reservoir studies as well as drilling results will be evaluated and implemented into the existing geological and dynamic models. This will serve as a means of enhancing the placement of future drilling locations and will help to reduce imminent risks for the complex Nakhla oil field reservoir.

Following this approach, Nakhla development phase II was designed and will be optimized continuously. Based on the good drilling and production experience of vertical hydraulic fractured wells it is planned to drill six (6) additional development wells in the same manner. The full-field simulation model adjusted by the G13-97 well results was used to perform a production forecast. Total production of 112 MMSTB was predicted and ultimate recovery estimates stand at 12.0%.

To extend the productive drainage area it is planned to continue the development with phase III. Additional seven (7) development wells were investigated in the existing reservoir simulation model (geol. model as of July 2002). Ultimate recovery estimates stand at 16% and cumulative production is predicted to be 152 MMSTB.

Considering the heterogeneity and low permeabilities of the Nakhla reservoir, hydrocarbon gas injection is predicted to have secondary recoveries of 13% and 19% for west and east regions respectively. Enrichment of the injection gas can increase the recoveries by 17%- 25%.

Water flooding is predicted to have good recoveries too, but major disadvantages of the simplified analytical model makes it difficult to extrapolate the results onto the real Nakhla reservoir. Furthermore, a CO_2 source is not known in the vicinity of Nakhla. Nitrogen flooding requires cost intensive generation plants and chemical processes can be denied due to the high reservoir temperature.

Based on these results and recommendations, a new full-field reservoir study based on compositional simulation will be performed incorporating 1) a new geological model post PSDM, 2) updated SCAL and relative permeability measurements as well as 3) accurate laboratory experiments on MMP and swelling test.

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