Petroleum Res. J. Vol. 18 (2005); P. 1-8, 7 Figs.

The Use of Complex Wells for Reserves Optimization in the Mabruk Field

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استخدام الآبار المعقدة لتحسين الاحتياطي في حقل المبروك

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يقع حقل المبروك الضخم في حوض سرت ويتكون من عدد 4 تجمعات للزيت، هي شمال المبروك – شرق المبروك– وسط المبروك وغرب المبروك ، لقد تم تطوير غرب المبروك تطويرا شاملا نظرا لوجود ميزات مكمنية واضحة به.

يتصف مكمن المبروك الجيري الواقع على عمق 3500 قدم بتغير شديد في السحنات مع تصنيف معقد نتج عنه عدم تجانس كبير للمكمن.

لقد بذلت محاولات عدة من قبل شركات متعددة منذ الخمسينيات لتطوير الحقل باستخدام الآبار العمودية ، ولكن بسبب السمك القليل الذي لا يتعدى 45 قدم ولقلة النفاذية كان أداء الآبار العمودية ضعيفا.

منذ سنة 1995 نجحت شركة توتال (CPTL) في استحداث طريقة لتطوير الحقل وزيادة الاحتياطي في حقل المبروك الغربي وذلك باستخدام تقنية حفر متطورة . إن استخدام الآبار الأفقية والجانبية سمحت بالتغلب على الإنتاجية الضعيفة وخففت من أثر عدم التجانس المكمني – عملية المحاكاة المكمنية استخدمت أيضا للتنبؤ بالمساحات التي قد تكون مسحت بضعف وذلك لغرض التخطيط للحفر البيني. ونتج من استخدام هذه الطريقة ازدياد تدريجي في تقدير الاحتياطي من 19% سنة 1995 إلى 28% اليوم.

المرحلة القادمة لتطوير المبروك هي استغلال الدروس المستفادة من غرب المبروك وتكييفها للأجزاء الأخرى من حقل المبروك وعلى الأخص شرق ووسط المبروك أيضا. إن مراجعة أداء الآبار والتحسن في الفهم الجيولوجي ستقود إلى تطورات أكبر في تصميم الآبار مستقبلا متضمنا هندسة الآبار والمسافات البينية واستراتيجية تحسين الإنتاجية وبرنامج حقن المياه.

هذه الورقة تناقش فلسفة التطوير المتبعة إلى حد الآن والتحسينات المستقبلية التي هي الآن تحت الدراسة لزيادة تحسين معامل المسترد النهائي في الحقل، كما تم تقديم نتائج أولية من هذه الدراسة المستمرة.

Abstract: *The Mabruk field, located in the Sirt Basin, is made up of four oil accumulations, namely North Mabruk, East Mabruk, Central Mabruk, and West Mabruk. The latter one, where fair reservoir characteristics were encountered, is the most extensively developed. The Mabruk carbonate reservoir, located at a depth of 3500 ft, is characterized by steep variations of facies together with a complex compartmentalization, resulting in massive reservoir heterogeneity.*

Several attempts were made by various companies since the late fifties to develop the field with vertical wells. But due to the small thickness (45 ft) and low reservoir permeability, the performance of vertical wells is generally poor.

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Since 1995, the approach used by Compagnie des Petroles Total Libye (CPTL) succeeded in developing and increasing the reserves in the West Mabruk field by using sophisticated drilling techniques. The use of horizontal and multi-lateral wells allowed coping with the low productivity and alleviated the impact of heterogeneities. Reservoir simulation was also utilized to predict the areas that will be poorly swept, and plan infill drilling. A gradual increase of forecasted recovery from 19% in 1995 to 28% today resulted from this approach.

The next stage of the Mabruk development will be to capitalize on the knowledge gained in West Mabruk, to adapt in the other parts of the Mabruk field (particularly the East and Central areas). Also, a review of the well performance and the improvement in geological understanding should lead to further improvements in future well design, including: well geometry, spacing, simulation and intervention strategy, and water injection scheme.

This paper discusses the development philosophy followed so far, and the foreseen improvements currently under study to further improve the ultimate recovery factor in the field. Preliminary results from the ongoing investigations are also presented.

INTRODUCTION: MABRUK FIELD HISTORY

The Mabruk field is located in Block NC 17 in the Sirt Basin (Fig. 1). The most sizeable oil volumes are located in the West and East panels of the Mabruk reservoir (Fig. 2), a carbonate member of the Heira marine shales, in the Paleocene. The West Mabruk (Fig. 3) has been so far the most extensively developed, due to its relatively fair reservoir properties (porosity of 15 to 25%, and permeability of 1 to 100 md). It is characterised by compartmentalisation of the structure, induced by heavy faulting. Large and unpredictable property variations were however, the main drawback in the field preventing a full-field development until the mid 1990's.

The history of West Mabruk started in 1959 when the field was discovered by Exxon, with well A01, encountering oil in the Mabruk and Garian reservoirs. Between 1959 and 1961, Exxon drilled 26 wells and implemented a five spot water injection pilot test (250m spacing) in West Mabruk. However, following

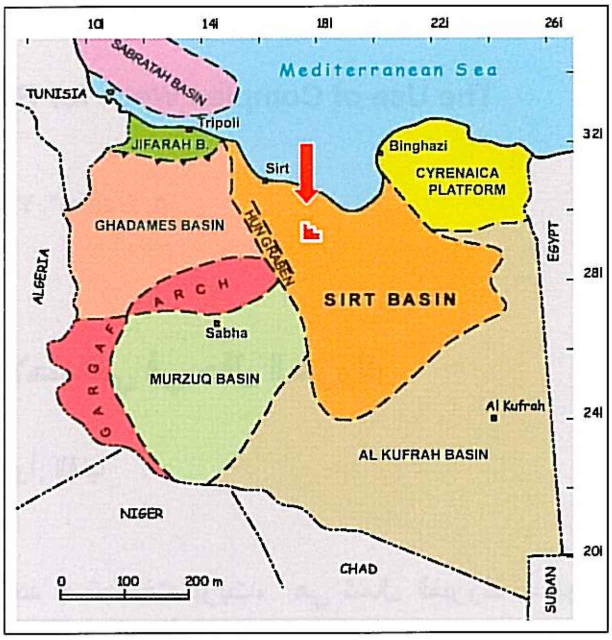

Fig. 1. Mabruk Block NC17 location.

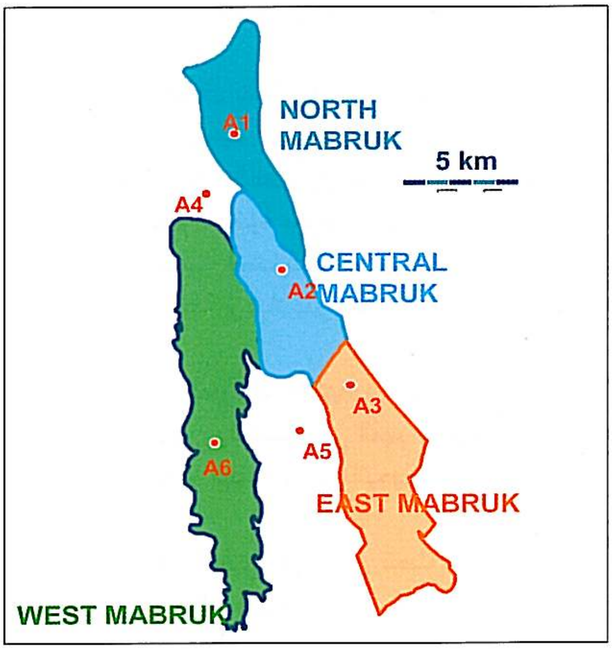

Fig. 2. Panel location and corresponding discovery/appraisal wells.

corrosion problems and early water breakthrough, the idea of a full development was given up. Sirte Oil Company resumed the development in 1982, shot a 3-D seismic, drilled 4 wells but, also abandoned due to the poor performance of vertical wells. Subsequently, Lasmo took over but gave up as well. Since the beginning, the IOIP estimate has decreased from 1 BSTB to about half this value. The real development of the field only started in 1995 with CPTL as an operator, and the use of horizontal and multi-lateral wells. The development included a two-year pilot phase prior to finalizing the development scheme. Water injection was implemented, first at peripheral locations, then in pattern, over the entire panel.

To date, almost 35 million STB of oil have been recovered from West Mabruk, and the current rate is around 15,500 BOPD from 35 producers, the reservoir pressure being maintained by 28 injectors. Of the 63 active wells, 26 are vertical (dating from the early development attempts), 26 are horizontal and 11 are multi-lateral. Horizontal and multi-lateral wells are drilled with 6" open-hole drains in the reservoir. Regular 3D model updates are carried out, with reservoir history-matches, in order to identify remaining opportunities (well interventions, re-entries or infill wells). Reservoir management is an integral part of the development, and the field is closely monitored with regards to well performance, water injection at voidage replacement, etc. The ultimate recovery factor for West Mabruk has progressed from 5% in 1988 to 28% today.

In the 7 years of development history by CPTL, a more precise knowledge of the Mabruk reservoir has been acquired. This will particularly help in the full development of the other panels, starting with the East and Central areas, planned this year (2004). Also, the influence of the reservoir characteristics on the wells completed in Mabruk is better understood, as presented in the next section.

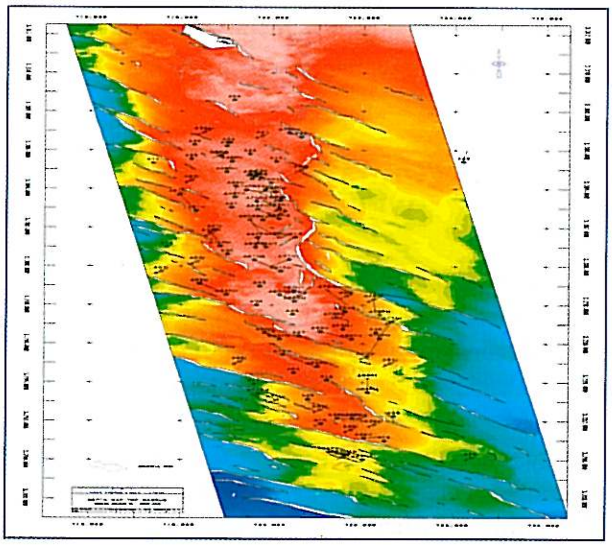

Fig. 3. West Mabruk structure showing the extent of fault panels.

THE MABRUK RESERVOIR: CURRENT KNOWLEDGE

The Mabruk reservoir is heterogeneous in both lateral and vertical directions. Rapid changes of facies and fracture networks are combined with a complex structural context, characterised by faulted blocks that are not necessarily recognisable from seismic data. The reservoir characteristics are degraded towards the flanks of the reservoir, which translates into a lack of natural (aquifer) support. The Mabruk oil is practically free of dissolved gas and provides no significant energy. This has motivated the decision to perform water injection at a very early stage in the field.

The lateral and vertical heterogeneity has influenced the chosen well design. By adopting horizontal and multi-lateral wells geometries, the chance of intercepting good facies or fracture networks was increased. See Figure 4 for a schematic of the current well design. Horizontal and multi-lateral wells, of open-hole design, have been used extensively since 1995 and contributed to the success of Mabruk so far. The benefit from fully open-hole horizontal and multi-lateral wells should not however, hide their drawbacks which are being recognised:

- The higher cost and drilling risks,
- The absence of stimulation in most of them (because of cost and feasibility considerations),
- The lack of future down-hole monitoring and well intervention capabilities (isolation or stimulation of specific drains or parts of drains), due to the open-hole nature of these wells.

The behaviour of horizontal and multi-lateral wells has actually not been as good as one could have expected in terms of productivity and developed reserves, especially in some parts of the field. Looking

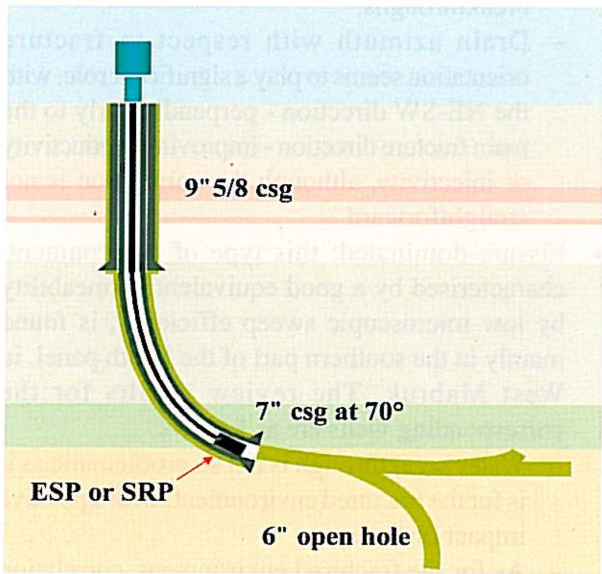

Fig. 4. Typical current well design used in the Mabruk reservoir.

at the historical performance of the West Mabruk wells, it is indeed possible to relate productivity, water-cut development and pressure support to the local reservoir characteristics. For this, a systematic review of all Mabruk wells was recently performed, which aimed at improving the understanding of the field, while also identifying possible data gathering and intervention opportunities. The review strongly suggested that the Mabruk wells performance depends on the prevailing fracture environment, as follows:

- Fracture-dominated: this type of environment characterises the production in the Northern panel of West Mabruk, where large fracture corridors have been recognised by fracture characterization studies. The effects on well performance and its link to well design, confirmed by the well review, are as follows:
  - Rapid water breakthrough is observed, due to the interception of open fractures. This affects the ultimate recovery, generally lower than for other environments,
  - There is no clear correlation between drilled length and well performance. The longer multi-lateral drains seem to actually perform worse, in terms of productivity and reserves, possibly due to the fact that a limited number of fractures are contributing to production. Productivity of vertical wells can be as good as for horizontal ones (when they intercept fractures). Reserves developed by multi-lateral and even horizontal wells is disappointing compared to vertical wells, due to the impossibility to isolate fracture-related water breakthroughs,
  - Drain azimuth with respect to fracture orientation seems to play a significant role, with the NE-SW direction - perpendicularly to the main fracture direction - improving productivity or injectivity, although the correlation is not straightforward.
- Fissure-dominated: this type of environment, characterised by a good equivalent permeability by low microscopic sweep efficiency, is found mainly in the southern part of the South panel, in West Mabruk. The review results for the corresponding wells are as follows:
  - Water breakthrough is not so problematic as it is for the fractured environment, with a positive impact on reserves,
  - As for the fractured environment, correlation between drilled length and productivity is not straightforward, and some vertical wells perform better than horizontal and multi-lateral wells. The poorer wells (in terms of productivity and reserves) are however vertical so horizontal geometry seems to increase the chance of intercepting good facies and fissure networks,
  - Productivity/injectivity is, again, possibly improved by NE-SW azimuth directions.
- Matrix-dominated: this environment, where no significant fracture of fissure network is encountered, is found mainly in the Central panel and the northern part of the South panel, in West Mabruk. The results of the well review for the concerned wells shows that:
  - As expected, water production is not yet a problem in this environment, and there is even an acceleration potential with infill drilling at tight spacing,
  - There is a much clearer correlation of liquid rate and productivity with the drilled length. Productivity is generally lower than for the fractured/fissured environment, but is clearly improved by drain length. Reserves are also well correlated with the drilled length,
  - Drain azimuth is not seen as an influencing parameter.

This improved knowledge led to the belief that well design should be adapted to the fracture environment, which resulted into a specific investigation: the Well Concept Study.

THE WAY FORWARD: STUDIES OF NEW WELL DESIGNS

A Well Concept Study was initiated in 2003, in order to optimise the design of future wells for the Mabruk further development (both on the East and Central undeveloped areas, and at infill locations in West Mabruk). The outcome will be a set of recommendations affecting not only future drilling practices but also completion and stimulation methods. The ability to effectively stimulate wells is seen as a major contributor to the success of the future designs. The methodology was to first define the reservoir requirements needed in each fracture environment:

- High productivity: as confirmed by the well review, for the fractured and fissured environments, efficient connection of the fracture/fissure network is needed, but does not necessarily require long drain length. On the other hand, long lengths are needed in matrix environments, as they provide larger productivity and reserves. Fracture plugging and matrix damage should be avoided or cured, through appropriate stimulation, avoiding large sections of the drain not producing, which would explain the poor performance of some of the longest existing wells,

- Efficient pressure support: well design should be optimised to allow pressure support while avoiding early water breakthrough. The currently low water-cut in the matrix environment points at the opportunity for smaller spacing. The distance should be optimised (larger in higher permeability or fractured/fissured environments than in poor permeability or matrix formations), but also a balanced production and injection between the reservoir layers needs to be obtained,
- Practical well intervention: the current 'fully open-hole' well design does not allow practical down-hole monitoring and water shut-off, despite the need for such interventions in many existing wells. The drawback has been lower developed reserves. Future well design should offer the possibility of such interventions so that reserves are maximised.

Based on the above analysis, the investigation of the following well concepts was proposed, the objective of the Well Concept Study was then to fine-tune the design parameters and determine their technical and economical viability:

- For a fractured medium: see Figure 5. The proposed design is that of a lined, cemented, perforated and stimulated single-horizontal well, oriented perpendicular to the fracture direction, with large spacing and line-drive. A large length would ensure that a maximum of conductive fractures would be intercepted, and save on the number of wells. Such large length would however require that each fractured zone is individually perforated and stimulated, so that production and injection is not affected by uneven damage. The cemented liner would also ensure selective water shut-off. The large spacing avoids early breakthrough.

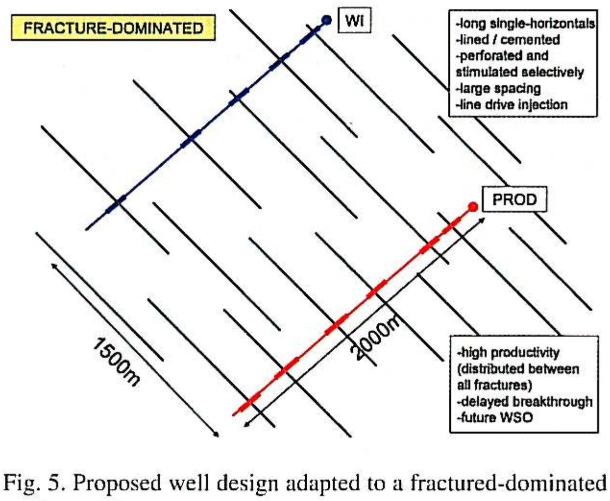

Fig. 5. Proposed well design adapted to a fractured-dominated environment.

- For a fissured medium: see Figure 6. The proposed design is a lined and cemented short trunk, possibly with one or two short open-hole laterals targeting each main pay zone, with large spacing and 5-spot injection. Large open-hole length is not necessarily required, but more than one drain would improve the chance of intercepting the fissure network. The cemented liner in the trunk would ensure future water shut-off (of a whole leg at a time, no isolation required within each leg), isolation of legs while drilling (to prevent differential damage between legs) and also a selective light stimulation program (acid or bleach circulation at TD). The 5-spot ensures optimum volumetric sweep for these relatively small wells.

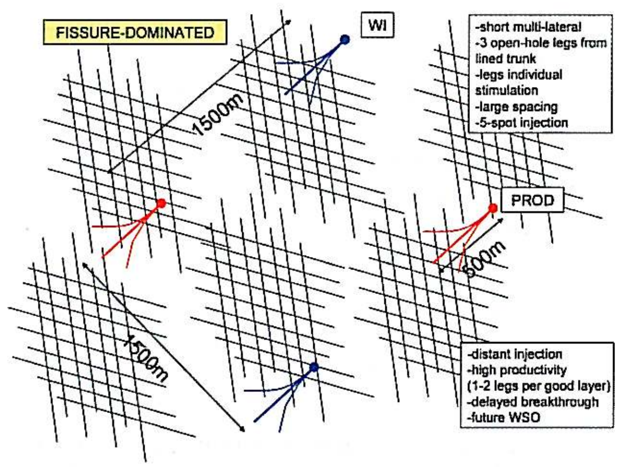

Fig. 6. Proposed well design adapted to a fissured-dominated environment.

- For a matrix medium: see Figure 7. The proposed design would be a lined, cemented horizontal backbone with open-hole lateral legs, drilled at small spacing, with line drive. Productivity would be ensured by the very large open-hole length, the spacing would be small enough to provide pressure support. The lined and cemented backbone ensures the same functions as the trunk of the fissured medium design, with possibility of leg isolation and selective stimulation.

Note that the Figures 5-7 are proposed designs and the quoted lengths/distances are qualitative

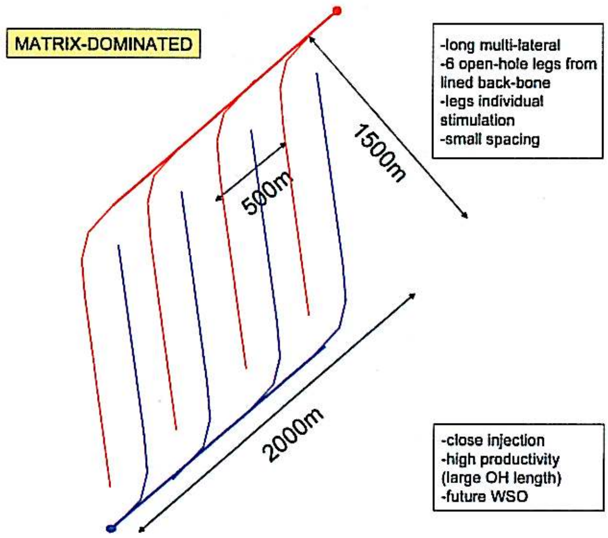

Fig. 7. Proposed well designs adapted to a matrix-dominated environment.

indications only, and were fine-tuned during the study. The technical feasibility of the 3 designs is also being investigated, with answers to the following questions:

- Technical and cost impact of drilling a sufficiently large diameter in the reservoir (8.5"), subsequently lined and cemented (7" liner), common to all three designs. This represents a major change compared to the current well design, for which the 7" liner is set at the top-reservoir, with an impact on costs,
- Feasibility of proposed geometrical parameters (lengths, angles, etc.), of completion and stimulation requirements, and cost impact,

The preliminary results of the study show that the proposed well concepts are technically achievable. Although they will cost more, the associated gain in productivity and reserves should largely compensate for the incremental CAPEX. The increase in productivity estimated by the study was very large, due to the adapted geometry but also the assumed effectiveness of stimulation methods. The gain in reserves was extremely encouraging. Recovery factors ranging between 40 and more than 50% were indeed obtained by sector model simulations. While lower recoveries are expected in full-field situations, figures in the range of 35 to 40% could still be expected in West Mabruk, compared to about 28% currently booked. This represents a gain of 7 to 12% recovery. The gain will be even superior in East-Central Mabruk, where only 16% recovery is currently expected. These results are however, subject to more in-depth studies, such as:

- Further sensitivities on reservoir parameters and uncertainties,
- A more detailed review of the technical feasibility of the new wells, with cost estimates, that will help fine-tune the economical evaluation,

However, nothing will better confirm the encouraging results than some field trials. As the success of the new designs will largely depend on the effectiveness of stimulation, it is proposed to test innovative stimulation methods in one or several existing horizontal or multi-lateral wells. Then, several pilots could be drilled in the field within a few months following the completion of the study.

CONCLUSIONS: REACHING 40% RECOVERY IN MABRUK?

The early years in the Mabruk development have been characterised by a lack of reservoir knowledge, in a field where lateral and vertical heterogeneities have a major effect on well performance. This lack of knowledge meant that reservoir properties could only be assessed as wells were being drilled. This, and other difficulties such as the presence of seismic 'blind' zones, made Mabruk a very challenging development. Since 1995, however, a lot of ground has been covered in the recognition of properties, their mapping, and the reduction of seismic risks, through data acquired in new wells but also by performing subsurface characterization studies. A better understanding of the fracture network, and its influence on well performance, was in particular a very valuable knowledge, which could subsequently be translated into improved well concepts, currently under evaluation.

The principles behind the choice of new well designs were motivated by the fulfilment of the main reservoir requirements ensuring efficient development of the Mabruk reservoir: the need for productivity (and injectivity), the need for effective pressure support (through water injection), and the benefit from an appropriate well life-cycle. This last point relates to the ability to perform data gathering and water shut-off activities in order to maximise reserves.

From the preliminary results of the study, the foreseen improvement in productivity from the new well concepts could be very significant, and is to be confirmed by field trials and pilots. It will certainly alleviate the need for large number of wells in the undeveloped parts of Mabruk (East and Central).

Even more importantly, the improvement in reserves is very encouraging. It shows that recovery factors from even difficult reservoirs such as Mabruk can match the highest levels obtained in the oil industry, reaching in this case the 40% level, possibly more. The application of such analysis and studies, and possibly the adoption of similar well concepts in other difficult fields could prove very attractive to the long-term development of resources in Libya.

Simple open-hole multilateral wells have been commonly drilled in the 1990s in different worldwide locations[1-7], some of them using similar "fishbone" geometries[4, 5]. The application of multi-lateral well technology has been particularly extensive in the Middle East, especially in Oman[5-7]. However, the Mabruk field in Libya has benefited from multi-lateral wells since the end of the 1990s, with an overall success[3].

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