

Reservoir Characterization and Management of an Aquifer Driven Reservoir –A Case History

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Summary

North Kadi oil field in North Cambay Basin, India has been under production since 1969. The hydrocarbon accumulation in the field is mainly in Middle Miocene sandstone of Kalol Formation having high permeability and strong aquifer support. The development plan of the reservoir had been drawn on the basis of simulation studies carried out at various stages. Recently, remodeling of the field has been done based on the re-characterization of the reservoirs. The simulation of new model was carried out in CMG's IMEX-2000 3-D 3-Phase black oil simulator for rational exploitation of the reservoirs.

Improved Oil Recovery (IOR) Scheme through in-fill drilling was formulated after updating the geological model. In-fill drilling of 33 locations was firmed up to achieve the optimal recovery. It envisaged 1.7% additional recovery of in-place oil in 20 years over the primary component of 31.23%. At the time of implementation of the scheme, the field had already produced 20% of 64.0 MMt (OIIP). All the 33 IOR locations were drilled in three years. As of now, the incremental production from IOR wells is 23% higher than envisaged. The in-fill wells have shown no interference on the performance of nearby wells within their past three years of production history, rather the overall field performance has improved with reduction of water cut from 67% to 64%.

The drilling and completion cost of the wells break-evened within 24 months. The IOR Scheme involving in-fill drilling rejuvenated the declining trend of a mature oil field and may lead to higher primary recovery than that of envisaged.

Introduction

North Kadi field is a major producer in North Cambay Basin, India. The field was discovered in 1968 and commercial production started in 1969 and under continuous production since then. Hydrocarbon accumulation has been established in multiple pay zones belonging to Early Eocene to Miocene Formations. Middle Eocene sandstone of Kalol Formation is the main producing reservoir having permeability of the order of 500 to 3000 md with strong aquifer support. It holds 95% of in-place oil of North Kadi field. The field development for Kalol pays have been done in phases on the basis of simulation studies. The geological models for simulation studies were conceptualized considering pay sands of Kalol Formation to have a number of layers subdivided on the basis of unit-to-unit correlation and all the layers were thought of hydro-dynamically in communication with. However, the sand bodies are separated by consistent non-reservoir coal/shale in between. Prior to the formulation of this improved recovery scheme, the geological model of Kalol reservoirs has been revised by integrating additional petro-physical, core and electro-log data. The revised model indicates that the pay units are not in hydro-dynamic communication. This necessitated to consider each unit as independent entity and hence treated separately for optimum exploitation. The revised classification of the pay units and their mapping has not only helped to resolve the apparent anomalous production behavior of the wells, but also helped in setting the strategy for rational exploitation of the reservoirs. Improved Oil Recovery (IOR) scheme by in-fill drilling was implemented during the period 2000-2003.

Geological Setup

Cambay Basin is an intracratonic graben trending NNW-SSE. In northeast, it is flanked by Aravali ridge, on its east and south by Deccan craton. It is bounded on both the sides by basement margin faults. Cambay Basin is divided into four tectonic blocks, namely Ahmedabad-Mehsana, Cambay-Tarapur, Jambusar-Broach and Narmada blocks from north to south (Fig.1).

North Kadi field is situated at the southern tip of 'Mehsana Horst', a well-defined structural feature in Mehshana-Ahmedabad block of North Cambay Basin (Fig.1). At Kalol level the field is doubly plunging anticline with two axial trends.

In the north, the structure abuts against Mehshana Horst and towards south it opens up to the aquifer. The stratigraphic succession of North Kadi field is similar to that of general stratigraphy of Mehshana area (Chandra et. al., 1969; Mehrotra et. al., 1980), however, the deposition of older sediments was not widespread as the area was comparatively higher at basement level. Even the deposition of Kalol Formation is highly influenced by the basement topography.

Reservoir Characterization

Kalol Formation of Middle Eocene age was deposited unconformably either on Cambay Shale or Mehshana Formation in North Kadi area. Earlier, the pays within Kalol Formation were divided into three units KS-I,



Fig 1. Location map of North Kadi and Adjoining oil field

KS-II and KS-III, and were believed to be hydrodynamically connected and accordingly the fluid contacts (GOC and OWC) were also considered common for all the pay units. This necessitated acceptance of a tilted water contact in the southern culmination for inexplicable reasons.

The new well data drilled up to year 2000 gave a new insight when a well showed the presence of gas in deeper zone, called KS-II and oil in upper zone, KS-I. A complete review of reservoir characterization was taken up with log correlation along with reservoir pressure data of various pay units. These have led to identification of five pays within Kalol Formation viz. USP (Upper Suraj Pay), KS (Kalol Sand)-IA, KS-IB, KS-II and KS-III from top to bottom. The KS pays are highly permeable (upto 3000 md) and holds most of oil-in-place. The average pay thickness varies from 15m to 4m in KS pay sands. The USP is comparatively tight. The reservoirs within Kalol formation have strong aquifer support from southern, eastern and western side.

The depositional environment of all the pay units within Kalol Formation have been brought out by various workers (Raju et. al, 1971, Bhandari et. al, 1971) besides the present remodeling exercise. The deposition of KS-III was mainly controlled by basement topography, i.e., the sands were deposited in pre-existing lows by the channel flowing from north to south. The coal/shale unit and occasionally high-density silty layer mark the end of this pay unit. The depositional environment of KS-II sand was fluvial and more precisely distributary channels. During the deposition of KS-IB unit the channels were mainly active in the southern part of the field. KS-IA is most widespread sand unit in the field having the best petro-physical character. The typical cylindrical shape in the electrical log motifs (Fig.2) along with sand quality and its distribution suggests that these sands are likely to have been deposited as laterally stacked channel sand in a braided system. The end of Kalol Formation is marked by a high density layer occurring at the top of Kalol

sand pack, known as USP. This layer clearly indicates the initiation of transgressive phase in the area.

Remapping of the newly identified pay units have been done, which not only brought out the prominent sets of faults, but also explained the rationale of different fluid contacts in different blocks (Fig.4). All these have led to formulate a new scheme of development and management of these highly permeable and independently aquifer driven reservoirs.

Field Development

From the very discovery of hydrocarbon in well NK#1, initial exploration and development was restricted in the southern part of the field around the discovery well. In later stage, field development activities were extended towards northern and western part. The field was developed in stages based on 3D-3 phase reservoir simulation studies carried out in the years 1981, 1987, 1989 and 1991. In the year 1995, the eastern extension of the field was established for Kalol Pays. The deeper prospects in the area were also discovered by

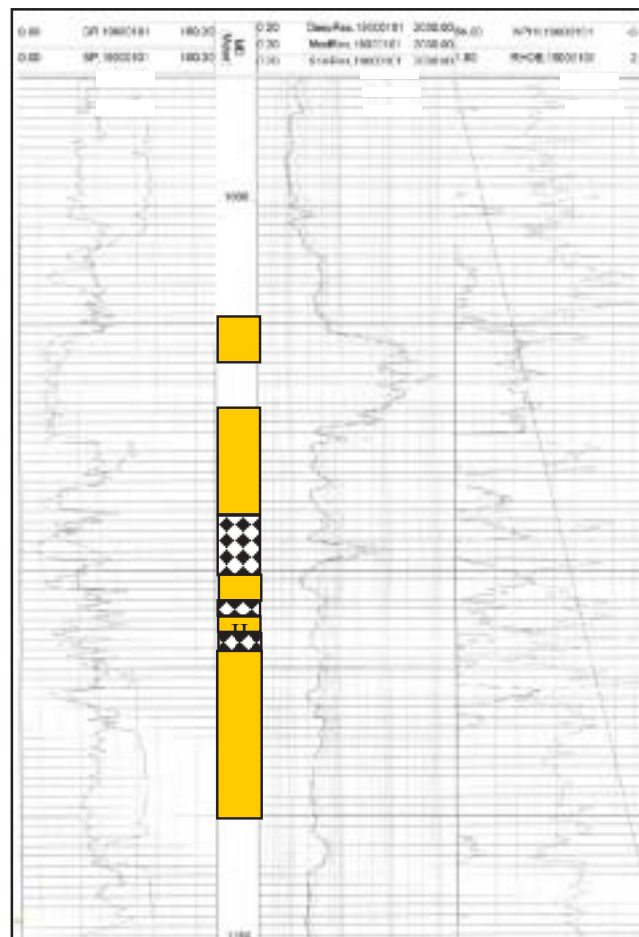


Fig.2 Log motif of a well in North Kadi field

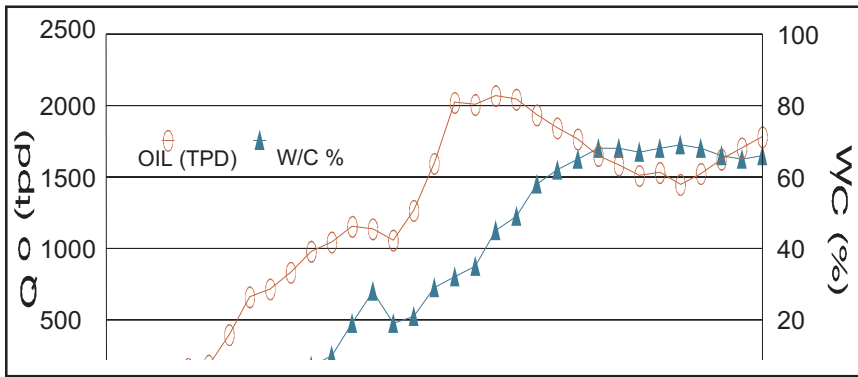


Fig.3 Production performance of N. Kadi field since inception (1969) to beginning of the scheme (2000)

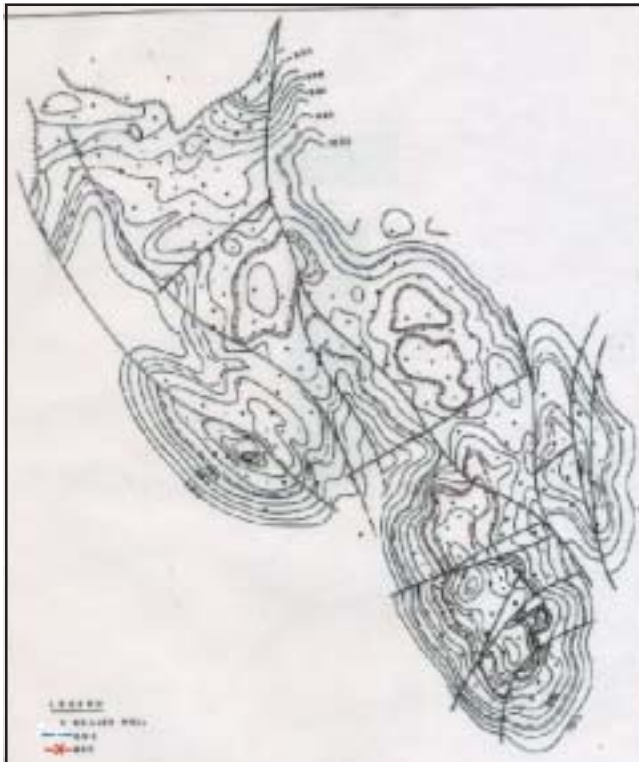


Fig.4 Structure contour map on top of sand

deepening of a number of wells. As on date, about 25% of field production is coming from this area alone. Beside these, the oil producers are being consistently worked over for water shut-off and repair of SRP to keep them flowing. The production performance of the field since inception till the implementation of scheme is shown in Fig.3.

Subsequently, in 1998 a Comprehensive Development Plan (CDP) for the entire field was conceptualized. Possibility of additional in-fill drilling was studied based on performance analysis of existing producers and identification of untapped areas. This led to release of 27 development locations for drilling to exploit Kalol pays. All the locations were drilled by March 2000. Many of the wells however, exhibited incoherent results both geologically as well as in fluid distribution as many of the wells were found to be placed in possibly swept out locales.

These adverse results of these CDP wells forced upon rebuilding the geological model of the field considering the data of 27 CDP wells along with previously drilled wells. The model was revised by integrating petro-physical, core and electro-log data along with production behavior of wells through out the field. The model indicates that the pay units are not in hydro-dynamic communication as believed earlier. Besides, a number of faults have also been picked up by integrating the well data with seismic and offset VSP data. The structural configuration at the top of KS-IA (topmost pay) is shown in Fig.4 after remodeling.

Simulation Model for Improved Oil Recovery

Although the reservoir is highly permeable along with active water drive, feasibility of in-fill drilling was further studied in August 2000 using updated geological model. Reservoir simulation study was carried out using CMG's IMEX-2000 3-D 3-Phase black oil simulator. Well-wise production data up to Dec'2000 have been considered for history matching. A reasonably good history match of wells could be achieved by adjusting the strength of numerical aquifer as well as rock and fluid properties. At the end of history match, performance prediction was run with in-fill locations. Also sector-wise production performance analysis was carried out keeping in view of structural disposition, development history and fluid distribution. It has been observed in the model that in-fill drilling was in favour of better recovery than that of maintaining of production from existing wells and working over sick wells in due course of time. The eastern sector, relatively underdeveloped merited most for in-fill locations. In other areas with left-over saturation, possibility of in-fill locations was also examined.

A number of prediction variants were studied for various probable locations. The prediction modes were run up to the year 2020. Optimization of in-fill locations was carried out with the primary consideration for economic viability. The prediction variant with 42 in-fill locations was found techno-economically suitable. However, it was decided to prioritize drilling of 25 better performing locations as observed in the simulator. The improved recovery scheme with drilling of 33 locations envisaged an additional recovery of 1.7% of OIIP in twenty years period over the base profile (Fig.5).

Performance Evaluation of IOR wells

A total number of 33 in-fill wells were drilled in a span of 3 years, which include 25 locations suggested by simulation model and 7 locations available at the time of study. Out of these, 2 wells were abandoned, one due to drilling

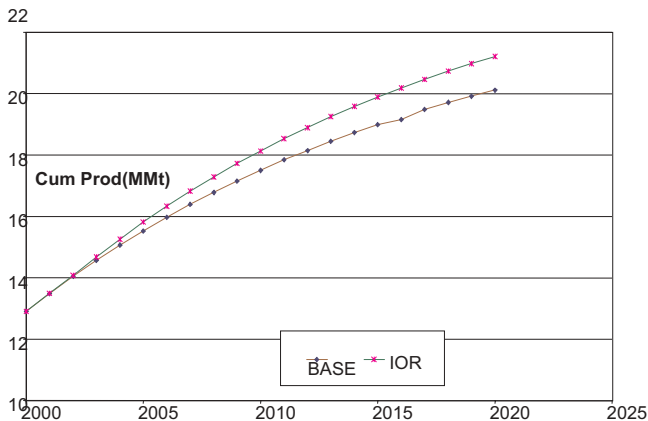


Fig. 5. Predicted IOR Profile with respect to Base Profile

complication and the other due to poor reservoir development. Further, one well was completed in gas zone developed within USP.

Most of the wells have been drilled in the eastern sector of the field, which is relatively less exploited. The field can be divided into five sectors based on prominent structural culminations; these are southern, eastern, central, western and northern (Fig.4). All the culminations have gas caps with different GOC. The OWC for all the sectors are also different varying from -998m to -958m. The gas caps in the eastern and western sectors are very small. In most of the cases shrinkage of gas cap has been observed with prolonged oil production, and five wells in northern sector have been drilled to exploit the left over oil from relatively un-drained area. Well wise performance analysis and the hitherto effect of in-fill drilling on the existing wells have been attempted. The sector-wise developments are as follows:

- The **eastern sector** was discovered as extension of field in 1996, based on abnormal production behaviors of wells in the marginal area. The delineation of the area depicted a number of faults resulting different fluid contacts in different blocks (Fig.4). The rise in water contact in close proximity of the field due to differential movement of fluid resulted by production from old wells has also been observed. Being a relatively untapped area, 12 in-fill wells have been drilled. All the wells are good producers having average oil rate about 16 tpd/well with average water cut of the range 2-10%, which are as per envisaged performance in the model. However, one well which is in close proximity to a fault, has been transferred to USP after producing with high water cut in KS-IA.
- The **southern sector** is the largest culmination of the field, where the discovery well NK#1 was drilled about 37 years ago. All the Kalol pays from bottom to top are developed. Twelve in-fill wells have been drilled in this sector. The area has a large gas cap with strong aquifer support from east, west and south.

The drilling results indicate no significant variation in structural levels as compared to the conceptualized geological model. However, in general, shrinkage of gas cap and rise of water contact have been observed. The production behavior of the new wells is more or less consistent after reaching water cut in the range of 20 – 40%. As far as nearby wells are concerned, in most of the cases no negative impact has been observed.

- In the **central sector** the initial gas cap was small which was later found to be absent in due course of production of oil below the gas cap. The performances of all three wells are poor irrespective of their pay thicknesses. The higher water cut in the wells may be due to preferential movement of water front from eastern edge. The structural low in the west seems to have played a major role for faster water movement.
- In the **western sector** only three wells have been drilled. Out of these, one well was abandoned due to drilling complication and other two wells are performing as per expectation.

In **northern sector**, the well wise performances are relatively poor as the oil is more viscous ($\mu_o = 150-200$ cp). Further, in the northernmost part, the main pay KS-IA is found pinching out and hence one location was recommended for cancellation. However, the well falling near the gas cap of north-central sector are good producers. One well in this sector too has been abandoned due to poor reservoir facies.

To sum up, the infill (IOR) wells in southern sector and eastern sector performed better than those in other sectors. But, in general the initial edge water for upper layers has changed into bottom water in due course of production. Identification of un-swept or partially swept out oil zones through reservoir characterization and simulation studies have helped in optimum placement of in-fill wells. Initially it was planned to complete all the wells with GP and SRP. However, meticulous planning of perforation and production

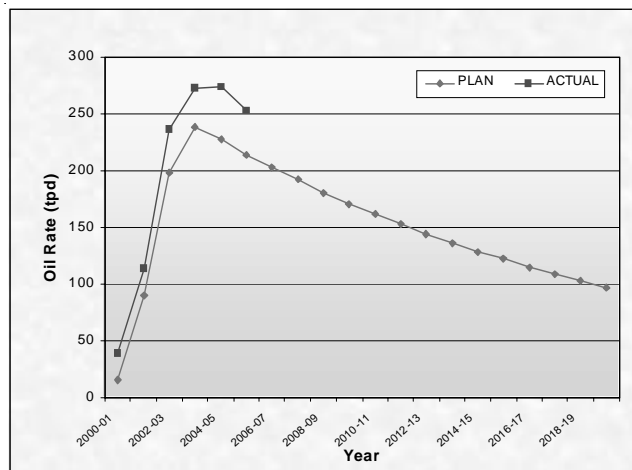


Fig.6. Actual oil gain vis-à-vis envisaged from in-fill (IOR) wells in North Kadi field

testing helped to complete most of the wells on self flow. As far as completions are concerned, till date, only 10 wells out of 33 have been completed with GP and SRP.

The oil gain envisaged from IOR wells vis-à-vis actual is shown in Fig.6. In addition to the remarkable oil gain from these IOR wells water cut has also reduced from 67% to 64% in last 5 years. (Fig.7).

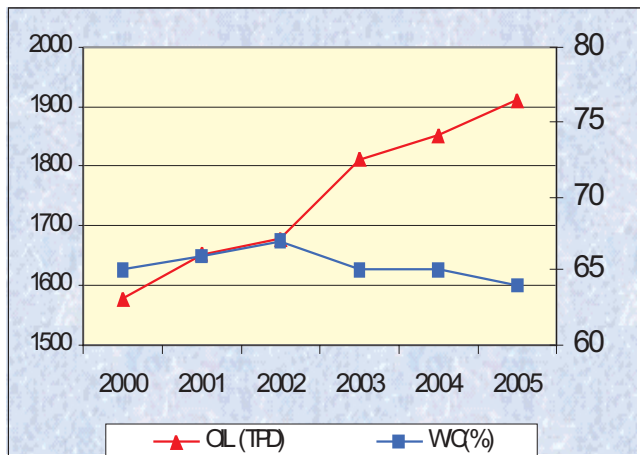


Fig.7. Production vs water cut since implementation of IOR scheme in N. Kadi field

Apart from IOR in-fill wells, workover jobs like water shut-off, zone transfer, re-completions and timely repair of SRP also contributed towards the enhancement of oil production from a mature field.

Conclusions

- Reservoir characterization and Continuous updating of geological model helped in rational development of the field.
- Reduction of well drainage radius (up to 200m) in a reservoir having good permeability and strong bottom aquifer supports proved to be successful and profitable.
- Pay thicknesses, residual oil saturation and structural positions played key roles in deciding the performance of the well.

- The oil contribution from the in-fill (IOR) wells is 23% more than that was envisaged in five year period.
- The cost incurred on completion of the wells was 25% less than the original estimates on account of cutting down drilling time, expenditure on completion and optimal perforations/ activation policy.
- The investment was paid back within 2 years period.
- The OPEX of these in-fill wells is also considerably low as more than 65% wells are on self flow.

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