Challenges and Risk Management Strategy for Enhanced Oil Recovery Projects in Carbonate Reservoirs of a Giant Field in Middle East

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Abstract

Late Cretaceous – Early Tertiary carbonate reservoirs of the giant Wafra Field, located in the Kuwait - Saudi Arabia Divided Zone, hold huge resource of heavy oil in 3 reservoirs, namely 1st Eocene, 2nd Eocene, and Maastrichtian. More than 50 years of primary production from these high porosity, moderate permeability carbonates has recovered less than 5% of this volume and the ultimate recovery is not expected to exceed 10%. Low primary recovery is attributed to oil gravity, viscosity and drive mechanism. Suitable EOR technology is needed to unlock these huge resources. In absence of any commercial analogs, application of EOR technology carries enormous risks in terms of technical viability, reserves recovery and resources commitment. Proper understanding of the reservoir and optimization of EOR technology are essential to mitigate these risks to a manageable level.

This paper will discuss the process used to meet various challenges and mitigate risks of EOR application in 1st and 2nd Eocene reservoirs through exhaustive screening studies, pilot projects and testing innovative technologies. Detailed screening study suggested the suitability of steamflood for 1st Eocene and both waterflood and steamflood for the deeper 2nd Eocene reservoir. Both projects have serious challenges due to reservoir nature, uncertainty in reservoir characterization, non-availability of fresh water, lack of proven technology for processing produced water for steam generation, disposal of excess produced water, fuel for steam generation, and safe environment for workers, public and wild life. These challenges make the EOR projects very high risk ventures. These risks are being managed through extensive G&G and simulation studies, exhaustive screening work and properly designed pilot projects. Five pilot projects are under implementation to resolve the number of uncertainties and manage associated risks in the high reward EOR process for these reservoirs.

This paper will share the strategy, work flow, uncertainty management and risk mitigation plan for these pilot projects and innovative technology being tested to manage challenges in full field application of EOR in carbonate reservoirs. Sharing of processes and innovative technology with industry will lead to success in mitigation of risks in EOR projects in carbonate reservoirs.
INTRODUCTION

Hydrocarbon resources in the Divided Zone (DZ) between The State of Kuwait and The Kingdom of Saudi Arabia are shared equally between the two countries. Kuwait Gulf Oil Company (KGOC), a subsidiary of Kuwait Petroleum Corporation (KPC) manages the 50% Kuwaiti share both in the onland and offshore parts of the DZ. Whereas, the 50% Saudi share is managed by the Saudi Arabian Chevron (SAC) in the onland part, and Aramco Gulf Operations Company (AGOC), a subsidiary of Saudi Aramco, in the offshore part. The shareholders carry out E&P activities through Wafra Joint Operations in the onland and through Khafji Joint Operations in the offshore part, respectively.

Wafra is a giant oil field located in the Divided Zone onland. Field location is shown in Fig.-1. Heavy oil was discovered in 1954 in two intervals within the Tertiary dolomite reservoirs of the field. A generalized stratigraphic column is presented in Fig.-2.

High sulphur heavy oil of 14° – 21° API is produced from highly porous and permeable dolomites of the Umm erRadhuma Formation of Paleocene to Early Eocene age. The reservoirs are divided into two units separated by bedded anhydrite. The shallowest, 1st Eocene occurs at an average depth of 1000’ and 2nd Eocene occurs at an average depth of 2000’. Solution gas drive with weak to no aquifer support is the main depletion mechanism for both reservoirs. Presently the reservoirs are producing below bubble point over major parts of the field. However, a strong water drive is prevalent in an isolated part of the 2nd Eocene reservoir, located in the southeast area of the field.
RESERVOIR CHARACTERISTICS

Wafra Eocene reservoirs comprise of dolomite associated with anhydrite (and gypsum towards the upper part). The anhydrite occurs in the form of nodules of varying sizes dispersed within the dolomite. Coalesced anhydrite nodules associated with dolomitized micrite and anhydrite cement often give rise to disconnected, lenticular beds. Historically these anhydrite ‘beds’ have been used to divide the reservoir into a number of ‘pay zones’. However, owing to their lenticular nature the anhydrite zones act more like baffles than barriers and the ‘pay zones’ within each of the two Eocene reservoirs are hydraulically connected. Eocene dolomite reservoirs have a characteristically high porosity and good permeability.

A thorough understanding of rock and fluid characteristics is essential for screening, evaluation and planning of any EOR process. Owing to the inherent complexities involved in characterizing carbonate reservoirs and the huge amount of untapped reserves, the Wafra Eocene reservoirs have seen concerted efforts towards reservoir description, acquisition of modern suites of logs and dynamic data, and adoption of state of art reservoir simulation technology since 1980’s. Current understanding of the reservoirs is derived from depositional models based on the principles of sequence stratigraphy. The joint venture has invested huge resources in terms of money, time and efforts in core and fluid sample acquisition and laboratory analysis before initiating the screening process.

PRIMARY PRODUCTION

Full field development was initiated in 1956 by drilling wells at 160 - 80 Acres spacing. Producers were initially completed barefoot in the topmost part of the 1st and 2nd Eocene reservoirs. This slow pace of development continued till Iraqi invasion in 1990. Production resumed in 1996 and development drilling resumed in 1998, with cased hole completions in multiple pay zones in each of the two reservoirs. After conducting development optimization study, infill drilling at 40/80 acres spacing was initiated in 2003 and continued up till 2006. Step out drilling, initiated in 2006, proved the extension of reservoirs outside the proven reservoir limits. Recent development drilling has been in the form of infill and step out horizontal wells in 2nd Eocene, with 40 acre spacing. However, 1st Eocene has continued developing with vertical wells at 40 Acre spacing, targeting shallower as well as deeper pay zones. Primary recovery techniques have recovered only ~4% of the effective oil in place and ultimate recovery is not expected to exceed 10%.

ENHANCED OIL RECOVERY POTENTIAL

Eocene reservoirs in the Wafra field have huge heavy oil potential. Present recovery from the Eocene heavy and viscous oil (14°-21° API and 30-200 CP viscosity) reservoirs is only 4% whereas, recovery from the deeper, relatively light and low viscosity (24° API, 2 CP viscosity) oil reservoirs has reached 30% of the original oil in place. Studies indicate that recovery of the heavy oil can be increased up to 40% of effective oil in place with implementation of a properly planned and suitable thermal recovery process. Steamflood is the leading thermal EOR process in the industry. The basic concept is that the injected steam enters the formation from the injectors, rises to the top of the formation, and progresses deeper in the reservoir toward the producers, forming a steam chest. With continued steam injection the steam chest expands downward, heating and pushing the oil. Producers produce heated oil and steam condensate ahead of the steam zone by a combination of mechanisms. As demonstrated in Figure-3, steam reduces oil saturation and increases volumetric sweep efficiency by:
- Viscosity Reduction (most important mechanism for heavy oils) and enhanced gravity drainage of heated oil
- Oil Thermal Expansion
- Steam Distillation.

**RISK ASSESSMENT AND MITIGATION PLANS**

In the absence of any commercial analog of steamflood and waterflood for heavy oil in carbonate reservoirs, it is a great challenge to determine technical and economic viability of the EOR processes. In view of the large uncertainties and high level of techno-economic risks involved, a progressive, phased approach was adopted in decision making process for full field implementation of EOR process. Figure-4 illustrates a phased approach adopted in decision making process for managing uncertainties and mitigating risks for this high risk high reward EOR strategy.

![Fig-3 Steamflood incremental recovery processes.](image)

**Fig-4.** Decision making process for uncertainty management and risk mitigation
A series of studies were conducted over a period of time for screening, pilot design, implementation and pilot evaluation process for full field EOR techniques. These include:

- EOR Options Study – 1999 (Screening Study)
- EOR Pilot Project Study – 2003
- Full-Field Reservoir Study – 2006 (geological model and history matched dynamic model)
- Geologic Model Update – 2009
- Development Strategy Study for 2nd Eocene update - 2011

A brief description of objectives, approach and conclusions of above studies is given below.

1. **Screening - 1999 EOR Options Study.**

   A comprehensive enhanced oil recovery options study was conducted in 1999 to determine the most feasible EOR technique for Eocene carbonate reservoirs in the divided zone. Huge resources were invested in conducting extensive laboratory work, geological studies and building reservoir simulation models. The study compared technical, economic and strategic benefits of steamflooding, waterflooding, polymer flooding, WAG and in-situ combustion. Screening study evaluated 1st and 2nd Eocene reservoirs, using simulation to compare field wide applications of different recovery processes.

   Following are key objectives, approach and conclusions of screening study.

   **Objective:** Compare the following five recovery processes:
   - Waterflooding
   - Polymer flooding
   - Steam flooding
   - Immiscible WAG (Water-Alternating-Gas) flooding
   - In-Situ Combustion

   **Approach:** Core and fluid sampling, laboratory core flood tests, detailed core analysis for fracture evaluation, detailed SCAL analysis and sector modeling.

   **Conclusions:** The screening study concluded that steamflood is the leading process for 1st Eocene. Whereas, steamflood and waterflood both are technically and economically viable options for the 2nd Eocene reservoir. Steamflood yields higher reserves and NPV whereas waterflood gives better investment efficiency due to lower CAPEX.

2. **2003 EOR Pilot Project Study.**

   **Objectives:** Validate steamflooding results from 1999 study and re-evaluate applicability of waterflooding and infill drilling.

   **Approach:** Full field modeling and history matching, sector modeling and analog studies.

   **Conclusions:** Steamflooding yields the best overall reserves and NPV whereas Infill drilling (enhanced primary) showed better reserves and economics than waterflooding.

3. **2004 - 2009 Steamflood Pilot Study.**

   **Objectives:** Select most suited pilot area, design pilot project and pilot evaluation process.

   **Approach:** Update 2003 full field model and history matching, sector modeling for selecting pilot area and
designing steam flood with thermal simulation model continuous updating the model using Steamflood pilot data for managing uncertainties in reservoir characterization and updating full field economics and risks.

4. **2006 Full Field Study.**

   **Objective:** Build a full field 2nd Eocene reservoir model for reservoir management optimization and reserves assessment.

   **Approach:** The history matched simulation model was used to assist with the design of the 2nd Eocene waterflood pilot.

5. **Development Strategy Study for 2nd Eocene.**

   This study is essentially an update of the 2003 EOR simulation with the 2006 geologic model.

   **Objective:** Compare three recovery processes, namely, infill drilling (horizontal and vertical wells), waterflooding and steamflooding.

   **Approach:** Sector models were extracted from the 2006 history-matched model and sector model results were scaled up to yield full-field forecasts.

   **Conclusions:** Steamflooding yields the greatest reserves and NPV whereas water injection gives higher discounted profitability index (DPI). Major risks were assessed and mitigation plans were prepared for effective execution of EOR process in the 2nd Eocene reservoir.


   Study was updated in 2011 with changed economic environment, high cost and high price scenario. Study confirmed 2008 conclusions.

**PILOTING STRATEGY**

Based on above studies, acquired data and historical assessment of production and reserves recovery a comprehensive piloting strategy was devised to address following key risks.

- Availability of fresh water for steam generation.
- Environmental risks associated with handling of produced water.
- Injectivity of steam over extended periods of time.
- Production and temperature response.
- Effectiveness of vertical barriers.
- Sweep efficiency.
- Early steam breakthrough due to suspected fractures.
- Scale and corrosion.
- CAPEX and OPEX.
- Well integrity due to high temperature and pressure of 2nd Eocene.
- Impact on well integrity and cement bond of wells of deeper reservoirs.

Six pilot projects were planned to manage uncertainties, mitigate risks and address challenges for full field development. A few of these have been completed and the rest are under implementation.
Project was implemented in 1999 to test steamflood application in 1st Eocene reservoir. The test concluded that:
   - Steam could be used as a leading technique for enhancing oil recovery from 1st Eocene reservoir.
   - Huff and Puff was found uneconomical due to high OPEX and low oil prices.

2. Small Scale Steamflood Test (SST).
Occurrence of fresh water is rare in this part of world and using external water for steam generation causes the problem of handling huge quantities of sour and contaminated water produced back. The only environmentally and economically acceptable solution is to use produced water to generate steam. There was severe uncertainty whether the oil stained Eocene produced water can be processed to make it suitable for steam generation. A single pattern, Small Scale Steamflood Test (SST) was implemented in 1st Eocene reservoir with following objectives:
   - Evaluation of technology for generation of steam from produced water.
   - Injectivity of steam into reservoir over long duration.
Test concluded that produced water can be used for steam generation with evaporator technology. This addressed a major risk on availability of water for steam generation and disposal of produced water. Steam injectivity into the carbonate reservoir over a long period of time was also successfully proved.
The SST was extended to develop an effective strategy for scale and corrosion observed in producers, post steam injection. Laboratory studies and field trials have helped to optimize metallurgy for down hole equipment and find suitable chemicals to address these issues, that could have been potential show stoppers.

3. Steam Injectivity Test for 2nd Eocene.
A pilot steam injectivity test was successfully performed to test steam injectivity into the deeper 2nd Eocene reservoir over a long period of time. Test confirmed steam injectivity in 2nd Eocene reservoir.

4. Two Large Scale Steam Injection Pilots (LSP).
Following success of the SST, two multi pattern Large Scale Steam Injection Pilots, one for 1st Eocene and another for 2nd Eocene reservoir are under implementation. Following are key objectives of these pilots:
   - Minimize reservoir characterization uncertainties especially with respect to dual porosity and dual permeability behavior.
   - Manage sweep efficiency uncertainties and develop risk mitigation strategy for full field application.
   - Evaluate CAPEX and OPEX for full field steamflood project.
   - Validate sectoral thermal model with data acquired by Large Scale Pilots and upscale it to full field thermal model.

5. Water Injection Pilot.
Second Eocene development study undertaken in 2008 concluded that in spite of higher NPV for steamflood, waterflood indicates higher profitability index compared to steamflood due to lower CAPEX and OPEX. In absence of any analogy of water injection in heavy oil carbonate reservoirs Second Eocene Water Injection Pilot (SEWIP) project has been implemented. The objective of pilot is to resolve following uncertainties due to specific nature of the reservoir.
- Displacement of heavy oil with water.
- Effect of fractures, vugs and baffles on overall injection and production mechanism.

**DEVELOPMENT STRATEGY**

A phased development approach from screening to full field development in synergy with other reservoirs was adopted to minimize risk exposure for high risk, high reward EOR projects. Figure-5 and 6 illustrate full field development approach for 1st and 2nd Eocene reservoirs respectively.

Fig- 5: A phased Approach from Screening to Full Field Development for 1st Eocene.

Fig- 6: A phased Approach from Screening to Full Field Development for 2nd Eocene.
SYNERGY WITH OTHER RESERVOIRS
Possible risks to existing wells, reservoir management for deeper reservoirs and steamflood synergy with 1st Eocene were also assessed. These aspects were included in uncertainty management and risk mitigation plan. Figure-7 shows relationship of 1st Eocene, 2nd Eocene and deeper reservoirs.
Detailed data acquisition programs for pilots and full field steamflood development were developed with the objective to manage above mentioned surface and subsurface risks.
Following discussion illustrates the process adopted for developing uncertainty and risk management plans.

Uncertainty Management Plan (UMP).
A full field Eocene reservoirs subsurface uncertainty management strategy was developed for overall EOR risk mitigation for Wafra heavy oil reservoirs.

Objectives:
- Generate a UMP Matrix.
- Evaluate Business Impact vs Resolvability
- Drives Surveillance Plans required to manage uncertainty and risks.
- Set up a clear plan for path forward work including contingency Plans, capture mitigation plans
- work plan to address resolution options including cost, time to get data, resourcing and value of information.

Approach:
A total of 66 uncertainties were identified, out of them 26 key uncertainties, 17 static and 9 dynamic, were ranked critical. Following table illustrates those key uncertainties.
Table-1: Major subsurface uncertainties

<table>
<thead>
<tr>
<th>#</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Remaining targetable oil</td>
</tr>
<tr>
<td>2</td>
<td>connectivity- interwell</td>
</tr>
<tr>
<td>3</td>
<td>Swirr Swmobile (controls water mobility)</td>
</tr>
<tr>
<td>4</td>
<td>Representiveness of LSP to full field development</td>
</tr>
<tr>
<td>5</td>
<td>Baffle/ barrier distribution</td>
</tr>
<tr>
<td>6</td>
<td>Faults and fractures- HIGH PERM</td>
</tr>
<tr>
<td>7</td>
<td>$K_v$</td>
</tr>
<tr>
<td>8</td>
<td>lateral heterogeneity (perm)</td>
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<tr>
<td>9</td>
<td>Permeability distribution</td>
</tr>
<tr>
<td>10</td>
<td>Steam barrier geometry</td>
</tr>
<tr>
<td>11</td>
<td>Top seals for steam chest</td>
</tr>
<tr>
<td>12</td>
<td>Effect of pore types on recover factor</td>
</tr>
<tr>
<td>13</td>
<td>near well Insitu dissolution and precipitation</td>
</tr>
<tr>
<td>14</td>
<td>calculation of $S_o$</td>
</tr>
<tr>
<td>15</td>
<td>flow unit thicknesses and number</td>
</tr>
<tr>
<td>16</td>
<td>formation water salinity</td>
</tr>
<tr>
<td>17</td>
<td>Max injection pressure (based on geomechanics)</td>
</tr>
<tr>
<td>18</td>
<td>steamflood volumetric sweep eff (was RF)</td>
</tr>
<tr>
<td>19</td>
<td>Source, mechanism, and strength of produced water</td>
</tr>
<tr>
<td>20</td>
<td>oil viscosity</td>
</tr>
<tr>
<td>21</td>
<td>Well injectivity</td>
</tr>
<tr>
<td>22</td>
<td>Changes in H2S and CO2 content with steam (facilities costs)</td>
</tr>
<tr>
<td>23</td>
<td>Residual oil sat</td>
</tr>
<tr>
<td>24</td>
<td>Zonal contribution- what is coming from each zone (steam into and oil produced from)</td>
</tr>
<tr>
<td>25</td>
<td>Wettability</td>
</tr>
<tr>
<td>26</td>
<td>Up-Scaling LSP simulation results to FF forecasts (water &amp; gas)</td>
</tr>
</tbody>
</table>

Forty six resolution alternatives were identified and ranked for above 23 uncertainties. The resolvability was classified as:

1. Impossible to resolve
2. Difficult to resolve
3. Moderately resolvable
4. Highly Resolvable
5. Totally resolvable.

Based on resolution alternatives (data acquisition type and level of ease). The business impact number was assigned to each uncertainty as: 0 - incidental, 1-Minor, 2-Serious, 3- Major and 4-critical. Key Uncertainties are defined as those with business impact of 3 and 4. Following tables illustrates UMP matrix definitions.

![Resolvability matrix](image-url)

Table-2: UMP Matrix for Key Uncertainties Business Impact vs. resolvability
An intensive, object based approach was adopted to manage the uncertainty matrix, develop resolution alternatives and formulate mitigation plans in the highly resolvable and moderately resolvable uncertainties categories.

In addition to subsurface uncertainty management plan, surface risk mitigation plans were prepared for each pilot to develop full field risk management plan. Risk management plan includes risk impact and potential mitigation. Following risks were assigned high priority for inclusion in the risk mitigation plan.

1. **Cost & Schedule Risks**
   i. Business Model
   ii. Market conditions
   iii. Regulatory issues
   iv. Forex uncertainties.

2. **Execution Risk**
   i. Development Pace
   ii. Incomplete or ineffective Project Execution Plan
   iii. Contracting strategy
   iv. Project Logistics.
   v. Organizational Capability.

**DECISION ANALYSIS FOR FULL FIELD EOR PROJECT**

Based on the anticipated risks, available extensive static and dynamic studies, a comprehensive decision analysis model was built to facilitate critical decision making on projects. This project is in feasibility and planning phase. A dialog process has been built between all stake holders and project team. The dialog process is illustrated in Fig-8.

![Decision Maker or Decision Review Board](image)

**Fig-8: A dialog process during planning phase.**
Process for critical decisions for Decision Analysis Package:

A comprehensive self-explanatory workflow will be utilized to provide input to economic model and decision analysis for critical decisions. Following is an example to illustrate flow diagram’s key components for a critical decision.

Fig-9: Work flow to reach critical decisions

Comprehensive Decision Analysis Work Plan has been prepared to enable project team and finally decision makers to optimize development of this huge, expensive and risky asset. Following are key components of decision analysis workflow.

1. **Framing - Frame the problem**
   - Guiding DOC/Charter - Ensure alignment among stakeholders regarding objectives and plans.
   - Issue raising/ Brain storming - Extensive list of issues than categorize into decision, uncertainties, value measures and others.
   - Decision Heirarchy - categorize decision (given, focus items, tactical).
   - Strategy Table - Generate alternatives by combining different focus decisions.
   - Spider diagram - Understand current state of decision quality.

2. **Deterministic Analysis**
   - Economic Engine - Inputs, Calculations, Value Measures (e.g NPV).
   - Understand key Values and key Drivers,
   - Deterministic Comparisons.
   - Deterministic sensitivity

3. **Probabilistic Analysis**
   - Cumulative probability.
   - Decision Tree.
4. **Evaluation**

Integrated reservoirs development strategy is being developed by updating reservoir models with data obtained from pilots, utilizing uncertainty and risk management plans and updating decision analysis package.

**CONCLUSIONS**

1. Huge heavy oil potential of the Eocene carbonate reservoirs of the Wafra field can be recovered with steamflood EOR process by properly planning projects, utilizing state of art decision analysis techniques, using integrated static to dynamic to economic modeling approach.

2. Screening studies need to be done with proper reservoir description, sufficient laboratory work and dynamic model validated with historical data.

3. Properly planned, executed and evaluated EOR pilot projects are key for planning a good full field EOR project.

4. Detailed and comprehensive history matched reservoir models, updated continuously with data acquired from pilot projects, are essential for executing

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