The Development Process; Zubair Reservoir, Raudhatain Field
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North Kuwait Plan Background
A conceptual development plan for North Kuwait area (NK) was approved with the objective of doubling production by 2005. The plan required an intensive drilling program among the NK fields and significant investment in facilities expansions. The Zubair reservoir in the Raudhatain Field will play a key role in the success of this plan. Three phases of development have been proposed. Phase 1 and 2, up to 2005, are designed to increase production through secondary recovery. The third phase, beyond 2005, is intended to extend the plateau through infill drilling and Enhance Oil Recovery (EOR).

Reservoir Geology
The reservoir contains four major horizons named Upper Zubair shale (UZsh), Upper Zubair Sand (UZsd), Middle Zubair Sand (MZsd), and Lower Zubair Sand (LZsd). In order to understand the depositional features and sand distribution/geometry of Zubair, a sedimentology study was carried out. This study impacted the well locations, injectors and producers, for Phase 1 development of the Raudhatain/Zubair reservoir.

Zubair Structure – the Zubair structure top is mapped by integrating the well tops with the seismic reflection from the Shuaiba/Zubair contact, thereby providing structure control at the top of the formation. Figure 1 shows the field location and the structure map of the Zubair top. The flank has limited well control. Structure maps of the four Zubair horizons were generated. Generally, the field has gentler sloping sides over the northeast area. Figure 2 is the stratigraphic table of the Zubair reservoir.

Deposition environments and sand geometry - The UZsh was deposited in a wave/shoreface and offshore-dominated environment resulting in sand channels that extend E-W across the anticline. The least well control, 2 drainage points, exit in this Zone. The UZsd were deposited in a tidal/estuarine environment in which the sand channels are stacked to produce a thick sequence of excellent quality reservoir. The sand is prevalent everywhere across the field. MZsd was deposited mainly in a tidal/estuarine environment. Three channel trends are observed. They are in vertical communication, however, they occur geographically in different areas. LZsd was deposited in a fluvial/mouthbar dominated environment. Lower quality sand is observed in
LZsd. Table 1 summarizes key reservoir rock properties derived from core and log analysis of the Zubair intervals.

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Table 1. Rock Properties

The highest quality rock is the UZsd sand with a lower quality observed in the UZsh and LZsd.

Reservoir connectivity – the sedimentological work indicates that fluid flow within the major producing intervals is governed by major field wide seals composed of mudrocks. It indicates also that vertical communication exists within stacked channel-fills especially in the UZsd. Smaller shale/mudrock beds cause local transmissibility barriers on a scale of up to one kilometer across. The major flow units cross the structure as channel-fills (generally E-W orientation) or near shoreface sands (generally N-S orientation).

Figure 3 is the Zubair RFT summary plot. Data regarding vertical connectivity is limited. Key observations from Figure 3 can be summarized as follows:

- Each main horizon has its own pressure regime. The shales/mudrocks appear to act as baffles to vertical pressure communication.
- Vertical connectivity through the UZsd, although good, does show small pressure variations associated presumably with thin shale stringers.
- The MZsd shows reasonable vertical connectivity through the sand sections.
- Pressure in the UZsd shows insignificant depletion between surveys, which is indicative of good pressure support.
- The MZsd and LZsd in particular, show significant depletion between surveys, which is indicative of poorer support.

Tar mats – it has been identified that there are two main tar mats that can be correlated across the field. The UZsd has the thickest tar mat (101 feet) consistently observed across the field. The MZsd tar mat thickness is approximately 37 feet. The LZsd is interpreted to have a patchy tar distribution. The sealing nature of the tar mats is not yet fully understood. These were found at around the original OWC’s.

Fluid distribution – with entrapment in the anticline geoform with 4-way dip closure, the Zubair fluids naturally separated out into four distinct producing intervals each with its own characteristic dynamic behavior. There are at least four original oil/water contacts that characterize the main producing intervals. It is observed that the tar mats overlap the original oil water contact’s (OWC’s) by tens of feet. Based on the post invasion open hole log data and pulsed neutron log interpretation, the current fluid distribution shows an uneven advance of the OWC around the perimeter of the field. Figure 4 shows the faulting pattern of the Zubair formation. Generally, the overall faulted pattern shows a NW-SE strike in the North half of the field, and NE-SW strike in the south half of the field. The impact of the faults on the fluid flow is not entirely understood. Throws are estimated to range from an average of 20 to 30 ft, to a maximum of 100 feet in the southwest perimeter of the field.

Fluid properties – a total of twenty-eight analyses of hydrocarbon samples from the Zubair reservoir horizons have been incorporated and reviewed. The fluid character is different in each unit. Significant fluid data scatter is observed in the saturation pressure and dissolved gas oil ratio (see Table 2). One oil type can be defined by the variation in properties. The variation in dissolved gas is reflected in the variation of saturation pressure. The MZsd produced GOR now exceeds the initial solution GOR due to depletion and a program to restrict the offtake is now being implemented. Figure 5 is a plot of the produced GOR trend with time (post liberation) for the MZsd.

<table>
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<td>LZsd</td>
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Table 2. Fluid Properties

Reservoir status
A significant number of surveillance data were collected after drilling 21 new wells after liberation (1991) in the Zubair reservoir. Those surveys include mainly pressure build-up tests (PBU), well tests, thermal decay time logs (TDT), production logging (PLT), shut in bottom hole pressures (SIBHP) and fluid samples in addition to the open hole log (OHL) data collected during the drilling phase. Those data have been analyzed and integrated with the available Zubair historical data to define the current status of the reservoir and to better define the first phase of the further development, Sea Water Injection Phase 1 (SWIPh1). This will provide 60 mbwpd to the Zubair reservoir for injection.

Pressure status – reservoir pressure data indicates that the pressure in the MZsd and LZsd is at or below saturation pressure. It is significantly above saturation pressure in UZsd and UZsh. Figure 6 is a plot of the pressure data trend of the UZsd showing low pressure decline over time although this reservoir has produced significant volumes of oil. In addition a period of gas injection took place between 1966-1981. It is observed from the pressure distribution in the major units that good areal connectivity exists. Even the poorer LZsd shows good areal connectivity with some of the inactive wells in the
east side of the LZsd showing decline in pressure associated with production of active wells some distance away in the central area of the reservoir.

Production status – historical production data shows that well production rates have in general declined from their initial rates. This is mainly due to the decline in reservoir pressure.

Material balance – material balance studies have been conducted for all the major producing zones in Zubair reservoir to understand the driving mechanisms and assess the degree of pressure support. As result the material balance indicated that aquifer influx is apparent in all producing zones with different intensity degree. The study indicates significant influx to the UZsd. This is supported by physical evidence observed of water encroachment. Relative to their STOIIP, the UZsd has very good aquifer support compared with the other units which shows limited support.

Initial Oil in Place (STOIIP) and Recovery Factor (RF) – probabilistic ranges for STOIIP and RF were determined. In the case of STOIIP low, mid, and high values were estimated for BRV, φ, OWC, and NTG. These estimates were entered into a Monte Carlo simulation to develop a probabilistic range of STOIIP values. Previous simulation studies and volumetric calculations indicated the most likely value of STOIIP. The field recovery factor was determined through the assessment of mobile oil fraction, based on connate water saturation (Swc), residual oil saturation (Sor) and estimates of vertical and areal sweep efficiencies. The Stiles technique was used to establish a range in vertical sweep efficiency for the UZsd and MZsd units using available core data. Estimates of the areal sweep efficiency were made based on the geological understanding of connectivity.

Water coning – a coning study was conducted in order to understand the performance of the UZsd wells under high rate production, i.e., 7mbopd. The development plan assumes new production wells in the UZsd will produce at rates higher than historic rates. The UZsd has bottom water drive and water coning is possible. However, the presence of shale and its lateral extent play a significant role in controlling coning. Classical and modeling techniques were used to define the critical rate at which coning occurs. The results showed that k_/k_ and stand-off from the OWC were the major factors which control water coning. The exercise showed that the critical coning rate for the UZsd could occur at 7 mbopd with a k_/k_ equal to 0.1 and would require a stand off of 50-90 ft. A single well simulation model was also used to estimate the critical coning rate. Sensitivities to oil production rate and the presence of shale were performed. The risk of coning was considered low at up to 7mbopd. In addition, the exercise recommended identifying UZsd wells with appropriate shales below perforations as candidates for short term additional production through bean-up.

Depletion plan

Short term plan:

- Restrict the offtake from the MZsd and LZsd to prevent the development of a secondary gas cap. The production rates are based on balancing the estimated influx to prevent any further reduction in reservoir pressure.
- To increase production of the intervals which have additional well and reservoir potential by drilling an additional 5 dual producers.
- To establish the feasibility of a peripheral water flood development.

The initial phase of injection, Sea Water Injection Phase 1 (SWIPh1), will test the initial development concepts and provide the foundations for further expansion. SWIPh1 will provide 60mbwpd by mid 1999. Injection will be into 5 new injectors on the periphery of the field; 2 injection wells in LZsd and 3 injection wells in MZsd. Existing wells will continue to be used.

Long term plan – it is anticipated that the development will continue to be a peripheral flood. However, the possibility exists that experience from SWIPh1 will indicate the need for changes, perhaps more towards pattern flooding in the poorer reservoirs, i.e., UZsh and LZsd. Surveillance and new well data obtained during the early development phase will provide the data in which to base the need for change.

Peripheral Flood Feasibility

Several reasons make it preferable to implement a peripheral flood in Phase 1 of the plan (SWIPh1), the reasons are:

- The reservoir quality is apparently high enough to enable a peripheral flood to be set up with manageable pressure loss from injectors to producers.
- The production history data to date indicates that good connectivity exists across the reservoir, which would permit a peripheral scheme to be initiated.
- Material balance and water movement to date in the major sand units indicates that aquifer influx is occurring, this will be supplemented with peripheral injection.
- Aquifer influx augmented with peripheral injection is likely to provide a very efficient sweep mechanism.
- Maximum use can be made of the existing well stock.

Profile summary and well numbers - ranged production profiles for the development plan were generated using a simple profile generator. The ranged profiles will help facilities planning. The inputs were:

- Target plateau rate and ultimate reserves
- Number of wells with time and field average well production rate (based on drilling program)
• Field average well potential was a function of field average watercut (based on lift curves performance and average PI data)
• Field average water cut with time curve assumed (using North Sea analogue data)

Well numbers were derived based on the producers and injectors necessary to achieve the plateau rate and maintain this rate up to 50% water cut. The actual performance of the Zubair reservoir will be clearer after implementing and assessing the performance from Phase 1 of the development plan.

**Watercut Performance** - The assessment of range in watercut performance is important for estimating production potential, required water injection quantities and water handling facilities with time. The process used in this study utilized analogue data of water oil ratio (WOR), from North Sea. The general trend for Zubair was positioned to fit some earlier simulation work, the current watercut performance and the known performance (expected better) of the Forties Field in the North Sea. A range in WOR was determined. This range in watercut-build was used to assess the range in future reservoir performance. Figure 7 illustrates the range in data and the cases assumed for Zubair.

**Operating Plan**

**Productivity Indices and Production Rates** – productivity indices were evaluated using pressure build up tests and wells vertical lift performance. Table 3 provides a summary of the actual and ideal productivity indices of the units. The data presents average values in the respective reservoir units across the field.

<table>
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<th>Unit</th>
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<th>PI, actual</th>
<th>PI, ideal</th>
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<tr>
<td>LZsd</td>
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<td>8.4</td>
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</table>

Table 3. Productivity Indices

It is observed that the UZsd reservoir has the highest productivity due to the quality of the sand. Production can be improved if skin damage is removed from the near wellbore region. An estimate of the typical production rate for the Zubair wells was made for the purpose of estimating the well numbers required to achieve Phase 1 plan plateau. The actual average PI values were used to estimate the production well rates.

**Injectivity and Injection Rates** – Injection will target MZsd and LZsd to provide pressure support. In those units the well potential is greater than the reservoir potential and can therefore utilize the injection support without further producers being drilled. The UZsd and UZsh can provide additional offtake without the need for injection in the short term period.

An injectivity study was conducted for the following purposes:

• To confirm that the target injection rates are achievable (10-20 mbwpd)
• To determine how much reservoir net sand is required to be completed to achieve the desired rates and assist in targeting the wells

Completion design of the injection wells and fluid property data as well as injection pressure available at the wellhead (2000 psi) during Phase 1 plan have been used in the exercise.

Assuming the MZsd conditions, it is estimated that the minimum injectivity index required to reach the target injection rate is 7 bpd/psi for seawater injection. The minimum net sand thickness required to reach the target injection rate was determined using the radial flow equation. Net sands of approximately 30 ft were estimated to be required. However, it was recognized that the wells may require to be fractured to achieve target rates. There is no fracture gradient data available currently for the Zubair. With the available injection pressure of 2000 psi for the SWIph1 injection wells, there is likelihood that the wells will not fracture. In this situation the injection rate may be limited. In Phase 2, The tubing head injection pressure is planned to be 3000 psi, as such the potential to fracture will be much higher. As such, the injection capacity will be much higher, however, the limit to injection is the erosion velocity. Injectivity tests to evaluate formation fracture pressure for MZsd and LZsd injectors are planned. If target injectivity is not initially reached, stimulation by acid or induced fractures will be considered.

**Injector Location Selection for SWIph1**

**Lower Zubair Injectors** – the least number of constraints in selecting the locations applies to the LZsd. Without a proven occurrence of a field-wide tar mat, the LZsd injectors are located beyond the original oil water contact per the highest structural uncertainty depth. By taking this approach, there is no concern of having any oil down dip of the penetration point.

**Middle Zubair Injectors** – the MZsd injectors (Figure 8) are more complicated with three channel trends identified. The prognosed typical vertical schematic for a MZsd injector is shown in Figure 9. The channels are considered the main flow units in the reservoir. A key uncertainty was the transmissibility through the tar mats. In order to mitigate against this, the target locations were sought to provide injection both above and below the OWC. If the MZsd structure is encountered at its maximum structural height, significant oil volumes could be left behind the well, i.e., down dip. In this case, it is recommended that injection be below the current oil water contact. It is anticipated that sufficient net sand will be available below the tar mat to allow...
injection to take place without jeopardizing the oil leg. There is at least 30 feet of net sand anticipated at all locations below the tar mat, to inject into. In order to assess what the fluid distribution will look like in new injection wells, a series of figures have been created based on the log data of the nearest existing wells. The picks are modified for the structure location of the new wells.

Perforation strategy – for the new producers the strategy is to maximize productivity to enable high rate wells to be delivered to high pressure separation at the facilities. The strategy require the following:

- Target all net pay sands.
- Blank intervals will be left between perforation sets to allow isolation for future profile modifications.
- In the UZsd completions, a minimum of 50 ft stand-off between the COWC and bottom perforation is required to postpone water conning.
- Stand-off from the UZsd gas cap is also required.

For the new Zubair injectors the perforation strategy aims to maximize matrix injectivity, conformance control is not an issue. The strategy requires the following interval selection:

- Minimum of 30 ft net sand below the OWC.
- Blank intervals will be left between perforation sets to allow isolation for future profile modifications.
- If operating experience shows the tar mats to be barriers then perforate in the oil leg (for MZsd injectors only).

Perforation technique – It is intended to perforate the UZsd and UZsh producer completion with casing guns. Injectors will be perforated in under balanced conditions to help mitigate damage in the near wellbore region.

Reservoir Operating Pressure – the optimum operating pressure for the unit is assumed to be at the current reservoir pressure. The reasons are:

- Desire to operate at an average pressure above the reservoir bubble point pressure. The MZsd and LZsd are essentially at saturation pressure and therefore it is not desirable to reduce the pressure any further.
- The reservoir pressures in the UZsh and UZsd are likely to fall slightly from their current pressure over the next few years due to continued and increase offtake rates. If the pressure in the UZsh and UZsd were reduced to the saturation pressures there would be a significant reduction in well potential. As such the plan assumes that reservoir pressures are maintained around the current values.

Surveillance Plan

Continued acquisition of surveillance data is a major aspect of the overall management of the Zubair reservoir. The impact of the sea water injection demands increased surveillance activity in the MZsd and LZsd. A surveillance and well activity plan has been constructed to meet the following objectives:

- To provide data on specific well productivity problems to help plan remedial actions.
- Improve understanding of reservoir performance in terms of pressure distribution, fluid movement, and volumetric sweep efficiency.
- To make sure that the resources (facilities and manpower) are available to cover the plan.

The surveillance plan include well tests, PLT Logging, TDT logging, PBU tests, SIBHP tests, pressure fall off tests (PFO’s), and a corrosion monitoring logging. The plan also include anticipation of well activities such as well workovers, rig or rigless, required for water shut off or other well problems. It is observed that a significant increase in the amount of surveillance and well work is expected in the future. This is necessary to assess the performance of the waterflood, and providing sufficient data on which to base remedial actions to enhance production and to help in planning further development.

Static and Reservoir Description Data- in addition to the routine surveillance data to be collected, static and reservoir description data from new wells will be taken. Down dip oil PVT samples from the flank injection wells is necessary to evaluate the properties of the oil in the flank area of the field. Preserved core will be taken in the oil legs for future SCAL work for determination of Sor, relative permeability curve determination and EOR studies. In order to optimize the performance of the waterflood, and maximize both the efficiency of the wells and the reservoir sweep, this data must be efficiently interpreted and effectively integrated.

Key Risk to Achievement of Plan

Major risk to the plan are anticipated as follows:

- Water Coning / Gas Fingering:
The plans require that wells be produced at rates higher than currently exist in the field. This increases the risk of coning. The facilities ability to handle increasing water could result in rate restriction and as such limiting the rate of new wells. The UZsd has a free gas cap resulting from a period of gas injection. The probability of gas fingering/coning is likely to be higher at higher offtake rates.

- Poorer Injectivity:
There is a little data available regarding the quality of the sands on the flanks of the field. However, the most appropriate areas have been targeted. If the tar mats are present at or near
completion intervals they might act as a barrier and make the flooding process inefficient. As such the injectors are being located to inject below the original oil water contact. It is possible that these wells could intersect a tar mat and low injectivity would be realized. The MZsd injection wells are located to provide some 30ft of net sand above the tar/oil contact to attempt to mitigate against the potential that the tar mats are a barrier. However, structural uncertainty exists in the flanks due to lack of well control. The possibility exist that significant oil potential may be encountered down dip, especially of the eastern flank MZsd injectors. It is intended that the drilling order be in the preferential sequence to maximize the data which could reduce these risks through modifying the final targets to minimize the down dip oil. It is possible that the eastern flank injectors might need to be considered for production if significantly more oil is found than expected.

- **Poor Reservoir Connectivity:**
The lack of data in the flanks of the field increases the possibility that the flanks, i.e. injectors, may be poorly connected to the crestal area. If the degree of aquifer influx is an indication of this then the poorest connectivity could exist in the LZsd, followed by the MZsd. The risk of poor connectivity in the UZsd is considered low.

**Contingency Planning** – based on the risks introduced above, several options could be adopted to maximize production rate in the medium term.

A. **Water and Gas Coning:**

- Consider recompletion of selected wells in the poorer zones, LZsd, to the higher reservoir potential zones, UZsd, in areas with the least opportunity of water/gas conning.
- Consider drilling horizontal wells sooner in the UZsd to mitigate the effects of water/gas coning.

1. **Poor Injectivity/Connectivity:**

- In the event of poor initial injectivity, initial fracturing of the wells with high pressure pumps may be required. Stimulation through acidizing may also need to be considered.
- The selection of well locations (especially injectors) for the SWIph1 plan has been made with the thought in mind that poor results in the target zones is a possibility. As such their suitability for other zones have been considered, particularly the UZsd.
- Consider a pattern development to efficiently sweep the poorer reservoirs if peripheral flooding is subsequently shown to be unsuitable.

**Summary and conclusions**

Development plans of fields can be set in different ways. The following points summarize the process adopted to develop the Zubair reservoir under peripheral waterflood:

- Define the reservoir geology through identifying the reservoir structure, depositional environments, sand geometry, reservoir connectivity and fluid distribution.
- Evaluate the reservoir fluid and rock properties. Properties might vary from one location to another. Estimate the range and most likely values to describe these properties.
- Use all the available surveillance data, static data, and reservoir description data to define the reservoir’s current status.
- Generate a range of STOIIP and recovery factors to provide a range in profiles. This will provide recovery uncertainty ranges to aid in facilities design.
- Define the depletion plan, operating plan, and surveillance plan. Phased implementation of the depletion plan is recommended to reduce the risk defined from reservoir uncertainty. Estimate the well numbers, producers and injectors, to meet the target plateau rate and to balance voidage replacement to maintain reservoir pressure and maximize the recovery factor.
- Define the key risks to successful achievement of the plan and generate contingency options.
- Locate wells to provide maximum flexibility against uncertainties, keeping in mind the objectives of injection and production, i.e., target the best locations that will provide the target production and injection rates.
- In the situation of significant reservoir uncertainty, the application of simple classical techniques, versus detailed simulation, is recommended.

**Nomenclature**

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Acknowledgments

The authors would like to thank KOC for their permission to publish this paper. They would also like to thank all those, including other Zubair team members, who have helped the Zubair team in their study effort.

References

Fig. 1 – Location map of Raudhatain Field and top of Zubair subsea structure map.

Fig. 2-Zubair zonation scheme.

Fig. 3-RFT data plot of Pressures vs. depth from three wells in Raudhatain Field.
• ZUBAIR CORED WELLS
• ZUBAIR WELLS

Fig. 4-Zubair structure map showing the faulting pattern. Note the identified original oil water contacts of the Zubair units.

Fig. 5-MZsd producing GOR trend (post invasion).

Fig. 6-UZsd pressure trend showing a low decline although significant amount of fluid volumes have been produced from this sand.

Fig. 7-Zubair most likely water cut performance.
MZsd INJECTORS

Fig. 8-MZsd injector locations. Note the channeling geometry effects in locating the injectors.

NOTE: There would still be at least 30 feet of net sand below the tar mat to inject into should the structure come in shallow to prognosis. This scenario will permit minimum reserve loss by injecting lower in the section.

Fig. 9-Example MZsd injector expected net sand development and related hydrocarbon/water intervals.