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Reserves Augmentation by Designing an Optimum Waterflood Pattern with Black Oil Simulator

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Abstract: *In petroleum production system, reservoir pressure is considered to be main source of hydrocarbon production from reservoir to the surface. With passage of producing time; fluids can only be lifted at the economic rates from subsurface to the surface by some secondary recovery method which sweeps remaining oil from the reservoir to improve its overall recovery.*

Waterflooding is the dominant fluid injection technique and is frequently applied worldwide secondary recovery process, which involves water injection in the oil formation under high pressure through an injection well to enhance oil recovery of the well(s) of interest.

Selection of optimum number of wells and their optimum location is a whip hand to plan and implement a successful waterflooding operation on a depleted reservoir to prevent the wastage of substantial capital investment. This involves efficacious and judicious selection of waterflooding pattern to augment the reserves. This study emphasizes on importance and effect of efficiently selecting an optimum waterflood pattern for primary production depleted reservoir "W" by simulating its performance for regular 5-spot & 9-spot patterns to acquire, best technical & economic match for subject reservoir for a particular injectivity, reservoir areal heterogeneity, direction of formation fractures, existing production wells and their spacing etc.

Where different opportunities involving a particular measurement or calculation are involved, there is no substitute for thinking out the best solution to the problem. The mistakes should be made on paper where an eraser can remove them, not in the field where someone must live with it.

I. Introduction

Using computer modelling to simulate hydrocarbon reservoir behaviour and recovery performance evaluation is an arduous task. The case study deals with developing a five spot and nine spot models on "Reservoir W" which is a solution gas-drive reservoir and its performance prediction using reservoir simulation. The study also includes comparison and economic analysis of five spot and nine spot models.

The tasks included are:

1. Construct reservoir models for primary recovery five-spot and nine-spot waterflood patterns using Black Oil simulator; ECLIPSE "E 100"[1,2].
2. Run reservoir simulations for all models.
3. Perform economic calculations for all models.
4. Compare the economics and simulation results by Dec. 31, 2041 for recovery, water cut, average reservoir pressure, oil production rate, gas-oil ratio, cumulative oil production, oil saturation, and pressure distribution between 5-spot and 9-spot patterns.

II. Reservoir Description

A conceptual petroleum production unit which is a solution gas-drive reservoir having anticlinal structure with 20,000 ft*11,000 ft*65 ft in size is to be simulated. "Reservoir W" is a heterogeneous layered reservoir with sandstone formation has an areal coverage of 5050.50 acres (20.439 km^2) and bulk volume (V_b) of 328,282.5 acre ft. The initial pressure of the reservoir is 3514.7 psia with solution GOR (R_{si}) =450 SCF/STB and its bubble point pressure is 1934.07 psia. The OOIP=2.23*10^8 STB. The formation compressibility is approximately 6E-6 sip at P_b pressure and thickness of reservoir is 65 ft.

Basic model Setup

The unit is approximated into 100 * 55 regular grids in horizontal layers and each cell is 200 ft in length; and 4 layers in the vertical direction (as 20 ft, 30 ft, 10 ft and 5 ft respectively) i.e.

Model Dimensions :100x55x4 = 22,000
Grid Type : Cartesian
Geometry Type: Block centred
Grid Dimensions
Layer 1 : 100x55x $(200)^2$x20 ft^3
Layer 2 : 100x55x $(200)^2$x30 ft^3
Layer 3 : 100x55x $(200)^2$x10 ft^3

Layer 4 : 100x55x $(200)^2$x5 ft^3

As the reservoir has an anticlinal structure so the grid top is not uniform. According to data provided by OGDCL, the grid block with minimum depth is at 6750 ft and with maximum depth is at 7150 ft in layer 1 as shown in **Figure 1.**

Fluid Saturations

Initial saturation distributions at reference depth of 7,000-ft depth are:

$$\text{Initial Oil Saturation} = S_{oi} = 78\%$$
$$\text{Connate Water Saturation} = S_{wc} = 22\%$$
$$\text{Critical Gas Saturation} = S_{gc} = 10\%$$

Porosity and Permeability

The "Reservoir W" consists of four formations with variable porosity, permeability and thickness of individual layer. Subject reservoir is heterogeneous and anisotropic i.e. there is regional change in porosity and directional change in permeability. Pore volume of the reservoir is 3.6371945*10^8 RB. According to data provide by "Company ABC" the minimum values of porosity and permeability are 0.1340 and 62.000 respectively, and maximum values are 0.1430 and 62.550 as shown in **Figure 2 & 3** respectively for layer 1.

The cross-sectional view of anticlinal reservoir showing variation of individual layer's porosity & permeability in x-direction is shown in **Figure 4**.

The permeability in x-direction (K_x) is same as permeability in y-direction (K_y) and vertical permeability (K_z) is $1/10^{th}$ of horizontal permeability. Thickness, porosity and permeability of the remaining three layers is provided in **Table 1.**

Table 1: Reservoir Properties

No. of Layers	Thickness (ft)	Porosity (fraction)	Permeability (md)
Layer-1	20	Grid Provided	Grid Provided
Layer-2	30	layer1*1.3	layer1*1.3
Layer-3	10	layer1*0.65	layer1*0.65
Layer-4	5	layer1*0.3	layer1*0.3

Average values of porosity and permeability are:
Average Porosity: 15.58 %
Average PERMX=PERMY: 70.08 md
Average PERMZ: 7.008 md

Relative Permeability & Capillary Pressure

Relative permeability verses saturation & capillary pressure data for gas, water and oil (three phase) is shown in **Table 2, 3** & **4.**

Fluid Properties

The "Reservoir W" will be set to produce by three mechanisms; primary recovery (no injection), five spot waterflood pattern and nine spot waterflood pattern. The reservoir produces oil of 41° API gravity with no sulphur, CO_2 1% and N_2 10% at isothermal conditions of 235°F. The connate water has specific gravity of 1, formation volume factor of 1.04569 RB/STB, compressibility of 3.31397E-6 sip and viscosity of 0.291387 cp at reference pressure of 1948.7 psia. Water salinity is 70,000 and gas gravity is 0.7 (with respect to air). **Table 5** gives comprehensive description of the fluid PVT data to be used during this simulation. The graphical representation of these PVT properties of live oil and dry gas is shown in **Figure 5 and 6**.

III. Primary Recovery

Firstly the "Reservoir W" is set to produce with its primary driving mechanism i.e. solution-gas drive. When the reservoir pressure is reduced as fluids are withdrawn, gas comes out of the solution and displaces oil from the reservoir to the producing wells. In "Reservoir W" ten production wells have been landed in to anticlinal formation and each of it is perforated in all the four layers. Each production well is set to open at a constant BHP of 1500 psia with maximum flow rate of 4000 STB/D with internal diameter available for fluid flow is 0.33 ft. Time span for simulation is 30 years.

There are ten production wells naming; "OSAMA", "P2", "P3", "P4", "P5", "P6", "P7", "P8", "P9", "P10".

Simulation was run for 30 years with strategy described in previous chapter and the results extracted from Report Generator Module of ECLIPSE E 100 are shown in **Table 6**.

Table 6: Primary Recovery Results

Average Reservoir Pressure-3139.28 psia
Initial Dissolved Gas-100.57 MMMCF
Average R_s-0.45 MSCF/STB

Average Oil saturation-0.78
Original Oil in Place-223.50 MMSTB
Oil Recovered-50.58 MMSTB
Recovery Factor-22.60 %
Current Reservoir Pressure-1516.7 psia
Current GOR-1.94 MSCF/STB
Current Oil Saturation-0.59445
Current Gas Saturation-0.18428
Current Field Oil in Place-173.301 MMSTB

IV. Problem Statement

The major portion of the "Reservoir W" is not recovered during normal depletion due to decline in pressure of the reservoir. Out of 223.50 MMSTB OIP (oil in place), 50.58 MMSTB (22.63%) has been produced after 30 years under solution gas drive reservoir/depletion drive reservoir; which has a weak driving mechanism and is currently unable to produce oil at economic rate due to decline in its reservoir pressure as shown in **Figure 7**. To recover the remaining oil from the reservoir, external energy is required. This required external energy can be given to the reservoir by any secondary recovery method such as waterflooding, during earlier production stage of "Reservoir W". After 30 years of production, 173.301 MMSTB remains untapped within the subject reservoir. Now oil can only be lifted at economic rate from subsurface to the surface, by some secondary recovery method which sweeps the remaining oil from the reservoir and increases the overall recovery of the reservoir.

So "Reservoir W" necessarily needs a source of artificial energy or pressure maintenance for generating handsome revenue for the "Company ABC" and to meet the energy demand of the market. So regular five spot waterflood pattern and regular nine spot waterflood pattern are developed alternatively to boost the pressure of the "Reservoir W" and to augment its reserves. Combination of technical and economic analysis will yield the optimum selection of waterflood pattern for "Reservoir W".

V. Regular Five Spot Waterflood Pattern

Waterflooding is implemented on "Reservoir W" by designing a regular five spot pattern. As the selection of possible waterflood patterns depends on existing wells that generally must be used because of economics. Pattern selection is constrained by the location of production wells. "Reservoir W" is developed for primary production on a uniform well spacing, so five spot pattern will be an intelligent selection.

"Reservoir W" is set to inject water at constant BHP of 2700 psia with 18 injection wells in a 180 acres well spacing, five spot pattern when pressure of the reservoir falls to bubble point pressure of 1934.07 psia. All the injection and production wells are perforated in each of the four layers with internal diameter available for flow is 0.33 ft. Time span for simulation is 30 years.

Ten production wells with constraints of constant BHP equal to1500 psia and maximum production rate of 4000 STB/D started working on 1 Jan 2011 under primary driving mechanism at initial reservoir pressure of 3514.7 psia. After 1.44 years (527.06 days) of production the reservoir pressure falls to P_b=1934.07 psia. At this time the 18 injection wells are triggered at above mentioned constraints. This can be done by using "ACTION" keyword in ECLIPSE E 100 as mentioned in Table 3.1. Until P_b, 11.668 MMSTB (5.22%) of oil has been recovered. For the next 28.56 years water will be injected. Maximum injection rate during injection span is 44.20 MSTB/D.

Simulation was run for 30 years with strategy described in previous chapter and the results extracted from Report Generator Module of ECLIPSE E 100 are shown in **Table 7**.

Table 7: Five Spot Waterflood Result

Average Reservoir Pressure-3139.28 Psia
Initial Dissolved Gas-100.57 MMMCF
Average R_s-0.45 MSCF/STB
Average Oil Saturation-0.78
Average Water Saturation-0.22
Average Gas saturation-0
Original Oil in Place-223.50 MMSTB
Oil Recovered-118.35 MMSTB
Recovery Factor-53.075 %
Current Reservoir Pressure-2333.6 Psia
Current Oil Saturation-0.3767
Current water Saturation-0.6297

Simulation results displaying oil saturation for regular five spot pattern in 3D view for t=30 years (2041) is shown in **Figure 8**.

VI. Regular Nine Spot Waterflood Pattern

Infill drilling has been done on “Reservoir W” for reducing the pattern size and to simulate its performance by regular nine spot pattern. Alternate to five spot, nine spot pattern is chosen on “Reservoir W” which is developed on a uniform well spacing to improve the recovery factor and field response to the waterflood.

This is done so by injecting water at a constant BHP of 3000 psia with 45 injection wells in a 92 acres well spacing, when pressure of the reservoir falls to bubble point pressure of 1934.07 psia. All the injection and production wells are perforated in each of the four layers with internal diameter available for flow is 0.33 ft.

Time span for simulation is 30 years. Ten production wells with constraints of constant BHP equal to 1500 psia and maximum production rate of 10,000 STB/D started working on 1 Jan 2011 under primary driving mechanism at initial reservoir pressure of 3514.7 psia.

After 1.44 years (527.06 days) of production the reservoir pressure falls to P_b=1934.07 psia. At this time the 45 injection wells are triggered at above mentioned constraints. Until P_b, 11.668 MMSTB (5.22%) of oil has been recovered. For the next 28.56 years water will be injected. Maximum injection rate during injection span is 154.971 MSTB/D.

Simulation was run for 30 years with strategy described in previous chapter and the results extracted from Report Generator Module of ECLIPSE E 100 for regular nine spot pattern are shown in **Table 8**.

Table 8: Nine Spot Waterflood Result

Average Reservoir Pressure-3139.28 psia
Initial Dissolved Gas-100.57 MMMCF
Average R_s-0.45 MSCF/STB
Average Oil Saturation-0.78
Average Water Saturation-0.22
Average Gas saturation-0
Original Oil in Place-223.50 MMSTB
Oil Recovered-150.55 MMSTB
Recovery Factor-67.51 %
Current Reservoir Pressure-2781.9 psia
Current Oil Saturation-0.3608
Current water Saturation-0.6400
Water Cut-0.9646
Cumulative Water Injected-533.98 MMSTB

Simulation results displaying oil saturation for regular nine spot pattern and depicting its individual performance in 3D view for t=30 years (2041) is shown in **Figure 9**.

VII. Engineering Comparison of Five & Nine Spot Pattern

Following text goes through the engineering or technical comparison of these two alternate flooding patterns simulated for “Reservoir W”.

1) Recovery Factor

Recovery factor is the pivotal and vitally important parameter in determining the engineering performance of five and nine spot patter for “Reservoir W”. For nine spot pattern, the field response to waterflood is more eminent as compare to five spot pattern. For first ten years of waterflood simulation, there is a substantial increase in percentage recovery for nine spot waterflood. However, at the later stages of waterflooding, the difference in recovery factor is narrow as grater percentage of oil has been swept away by the injection fluid. From above figure it is authenticated that, for “Reservoir W”, regular nine spot pattern gives greater recovery efficiency than regular five spot pattern.

2) Field Pressure

The declining reservoir energy by solution-gas of limited extent in “Reservoir W” is supplemented by waterflooding with either five spot or alternatively by nine spot pattern. Initially the pressure in both five and nine spot pattern increases due to injection of water, but with passage of waterflooding the total flow rate in reservoir approaches to injection rates and pressure is approximately maintained. That is why, waterflooding is also called pressure maintenance. Also the injection into a solution gas-drive reservoir usually occurs at injection rates that cause repressurization of reservoir. In nine spot pattern, 45 injection wells are installed in

"Reservoir W" in contrast with five spot; in which 18 injection wells are used. That's why pressure is higher in case of nine spot than in five spot pattern.

3) Cumulative Production

There is greater cumulative production in regular nine spot pattern in comparison with five spot pattern. More quantity of injection fluid is available and at different location of "Reservoir W" gives greater is to be produced. The amount of water injected will dictate its percentage of total swept area to total areal coverage of the subject reservoir i.e. areal sweep efficiency is more. So in turn the amount of oil produced at given simulation time is more in nine spot pattern than in five spot pattern.

4) Oil Production Rate

There are total of 10 production wells with BHP of 1500 psia in each of the five spot and nine spot pattern, but for five spot pattern each of these production wells are open to flow at surface flow rate of 4000 STB/D and at 10,000 STB/D for nine spot pattern. So initially the oil production rate is much higher in nine spot pattern than in five spot pattern. However, with passage of time, the oil production rate for nine spot becomes less than of five spot, as greater quantities of oil has been recovered in earlier life of the project. At the end, the production rates of both the flooding patterns are nearly equal to one another.

5) Water Injection Rate

Injection rates must exceed reservoir withdrawals if the reservoir pressure is to increase. At higher injection rates, the oil bank develops more rapidly and reservoir response occurs much sooner. As for "Reservoir W", the nine spot pattern has higher ratio of injection to production wells, subsequently it has greater values of injection rate than that of five spot pattern. At early stage if injection, high injection pressure is needed to produce oil at respective production rates of five and nine spot, but with injection time the reservoir is repressured so less injection rate is sufficient to produce oil at assigned production constraints.

6) Cumulative Water Injected

Waterflood performance highly depends upon volume and location of injected water. During first 1.44 simulation years of production, the injection wells are closed. When reservoir pressure drops to bubble point, the injection wells are triggered. The nine spot pattern requires greater quantities of water to be injected in "Reservoir W" to maintain high production rate than five spot pattern as shown in **Figure 10**.

7) Water Production Rate

After displacing oil, water injected at a particular rate into reservoir is produced at injection well. When the production wells are watered-out they are unable to produce oil at desirable rates. The water production rate for nine spot is very large than that of five spot due to its greater number of wells, high injection pressure and greater deliverability of production wells.

8) Cumulative Water Produced

The water injected in to reservoir will displace the oil and eventually reaches the production well where it outcome from the production well. For nine spot pattern very large quantities water is injected. The injected water after sweeping the oil enters the production well. For five spot pattern the increase in production of water with simulation time is less steep than in case of nine spot pattern as shown in **Figure 11**.

9) Water Cut

The fractional flow of water is an important parameter in evaluation of recovery performance of five and nine spot pattern. The fractional flow of water rises abruptly for nine spot pattern as soon as the water injection is commenced. This might be because of smaller well spacing of water injection and oil production wells. For five spot pattern as the injection and production wells are far away from each other having greater well spacing and less number of water injection wells so fractional flow of water increases steadily in comparison with nine spot pattern. At the later stages waterflooding, much of the oil has been recovered so percentage of water flowing in the reservoir is much larger than of oil so the F_w rises above 90% for both the flooding patterns

10) WOR

The economic limit of most of the waterflood projects is based usually on water-oil ratio i.e. the amount of produced water associated with produced oil. It is obvious from the **Figure 12** that regular nine spot pattern has higher values of WOR as compared with regular five spot pattern.

11) Water Saturation

As soon as the waterflooding is initiated on “Reservoir W” after its primary recovery either by five or nine spot pattern, the saturation of water begins to increase. For nine spot pattern, this increase is more than in five spot pattern owing to greater water injection wells and their optimum location. After 10 years of waterflooding, more than 50 % of water saturation has been developed in the pores of “Reservoir W” for both five and nine spot waterflooding pattern.

12) Oil Saturation

During waterflooding a reservoir its oil saturation is reduced due to withdrawals. Water sweeps a percentage of oil depending upon the nature of project, but a fraction of oil remains stranded in the porous media due to different injection schemes for developing reservoir and inherent properties of the reservoir such as horizontal and vertical heterogeneity, bypassing of injection fluid, low permeability streaks, anisotropy, wettability and capillary pressure. For five spot pattern the amount of unswept oil is more than that for nine spot pattern.

Engineering Comparison of Five & Nine Spot Pattern: Results

The complete engineering analysis and performance evaluation of “Reservoir W” using regular nine spot waterflood pattern and of regular five spot waterflood pattern with the help of Black Oil Simulator explicitly shows that the regular nine spot pattern gives greater recovery efficiency [**Figure 13 & 14]** and is advisable to plan a nine spot waterflood injection scheme for this reservoir. However, as nine spot waterflood pattern has more injection wells comparable with five spot pattern which obviously requires high capital investment, so economic analysis will be the conclusive and decisive factor in ultimate selection of waterflooding pattern on “Reservoir W”.

VIII. Financial / Economic Comparison of Five & Nine Spot Pattern

In today’s world, economics control the decision making process for future projection. For the last two decades, energy supply has suffered from a series of oil crises e.g. BP oil spill in Gulf of Mexico (2010). This forces reservoir and production engineers to direct their attention to study the economic performance of oil and gas fields. The study utilizes the data generated by the Black Oil Simulator primary recovery, regular five spot and regular nine spot pattern for economic evaluation of the production projections and assessment of these investment opportunities to select the economically optimum case for profit generation.

The tasks included are:

- Developing an economic model based on net cash flow concepts to study the different alternatives for field development.
- Calculating Before & After-Tax Net Cash Flow for the economic model
- Studying the effect of time value of money by introduction of an arbitrary discount rate
- Economic Comparison of all the investment opportunities

Case A: Economic Analysis of Base Case (Primary Recovery)

The Parameters shown in the **Table 9** are assumed for oil production under primary recovery for 30 years in the economic model. The operating cost of the base case is assumed in accordance with current operating conditions provided by “Company ABC”. The initial investment for primary recovery is 210 million dollars. The economic calculations of the base case are summarized in the **Table 10 & 11**.

Table 9: Primary Recovery

Economic Parameters & Worth
Parameter-Worth
Oil Price [Brent crude oil]-90 ($/bbl)
Royalty-20%
State Taxes [Severance/Ad valorem]-12%
Operating Cost-10 ($/bbl)
Over head % of Operating Cost-30%
Capital Investment-200 (MM$)
Bonus &Leasehold Cost-10 (MM$)
Income Tax Rate-30%
Discount Rate-10%

Case B: Economic Analysis of Augmented Case
(Five Spot Waterflood Pattern)

The Parameters shown in the **Table 9** are assumed for oil production and water injection methods in the economic model.

Table 9: Five Spot Waterflood

Economic Parameters & Worth	
Parameter	Worth
Oil Price [Brent crude oil]	90 ($/bbl)
Royalty	20%
State Taxes [Severance/Ad valorem]	12%
Operating Cost for Incremental Oil	10 ($/bbl)
Operating Cost for Water Injection	2 ($/bbl)
Injection Water Treatment Cost	3 (MM$)
Cost of drilling one injection well	6 (MM$)
Cost of drilling 18 injection wells	108 (MM$)
Cost of one Water pump (triplex plunger Pump)	10 (MM$)
Cost of 9 water pumps for 18 injection wells	90 (MM$)
Cost of auxiliary equipment	1 (MM$)
Over head % of Operating Cost	30%
Capital Investment	402 (MM$)
Bonus &Leasehold Cost	15 (MM$)
Income Tax Rate	30%
Discount Rate	10%

The operating cost for augmented case is assumed same as the current operating cost to reflect the fact that the incremental production will enjoy the existence of surface facilities capable of treating the additional production with virtually no operating cost. The initial investment for regular five spot pattern is 417 million dollars. The economic calculations of the five spot waterflood are summarized in the **Table 12, 13 & 14**.

Case C: Economic Analysis of Augmented Case
(Nine Spot Waterflood Pattern)

The Parameters shown in the **Table 15** are assumed for oil production and water injection methods in the economic model.

The initial investment for regular five spot pattern is 713 million dollars. The economic calculations of the augmented case are summarized in the **Table 16, 17 & 18**.

Economic Comparison of Five & Nine Spot Pattern: Results

The calculations show the economic analysis and productivity of three different investment proposals. The best measure of the economic worth of the investment proposals is their ability to generate profit.

The net present value for Case A (base case) is 875.757 million dollars as shown by the discounted cash flow calculations at the discount rate of 10% if "Reservoir W" is produced under its primary driving mechanism for 30 years with capital investment of 210 MM US $. However, if Case B (five spot waterflooding) is practically implemented on "Reservoir W", then the net present worth of this investment opportunity will augment from 875.757 MM US$ to 1632.196 MM US$. Although the initial investment required for this is 261 MM US$ more than that required for base case, the profit generated is phenomenal i.e.756.439 MM US$ more than primary recovery.

The Case C (nine spot waterflood) does not show fruitful results as compared with five spot pattern. The net present value decreases from 1632.196 MM US$ to 1561.026 MM US$. The initial investment required is very large i.e. 7.13 billion US dollars. Also the cash flow for last three years is negative; the operating expenses exceed the revenue generated. **Figure 15 & 16** shows the comparison of NPV and capital investment for all the cases.

Table 15: Nine Spot Waterflood

Economic Parameters & Worth	
Parameter	Worth
Oil Price [Brent crude oil]	90 ($/bbl)
Royalty	20%
State Taxes [Severance/Ad valorem]	12%
Operating Cost for Incremental Oil	10 ($/bbl)
Operating Cost for Water Injection	2 ($/bbl)
Injection Water Treatment Cost	4 (MM$)
Cost of drilling one injection well	6 (MM$)
Cost of drilling 45 injection wells	270 (MM$)
Cost of one Water pump (triplex plunger Pump)	10 (MM$)
Cost of 22 water pumps for 45 injection wells	220 (MM$)
Cost of auxiliary equipment	2 (MM$)
Over head % of Operating Cost	30%
Capital Investment	696 (MM$)
Bonus &Leasehold Cost	17 (MM$)
Income Tax Rate	30%
Discount Rate	10%

IX. Conclusion

The engineering and economic study depicts that the "Reservoir W" necessarily needs implementation of waterflooding The economic model developed for primary recovery, regular five spot waterflood and regular nine spot waterflood shows that the economical investment opportunity will be five spot waterflood, as it generates handsome revenue and profit for "Company ABC". Although the recovery efficiency of nine spot waterflood is large, but its high capital investment and low profitability makes it an unfavorable option for subject reservoir. But the crux is that the oil and gas exploration and production are inherently probabilistic. By their very nature they include large element of risks and uncertainties. That is why petroleum exploitation is always an exciting and challenging game----a game of chance but also of change.

X. Recommendations

On the basis of this study, I recommend the following:

- Reducing the pattern size of either five or nine spot pattern to 40 acres and investigating its impact on recovery.
- Selective plugging of either layer(s) can reduce the early breakthrough at production wells
- Delve the effect of salinity on waterflooding for improving recovery efficiency.
- Investigate the technical and economic impact of installing sucker rod pumps on each of the production wells.
- Adopt a monitoring plan for monitoring of production or pressure data e.g. installing SCADA on the production facility.
- Streamline simulation can be helpful in better field management and pattern balancing.

XI. Acknowledgement

I am grateful to operating company OGDCL for providing technical data, Schlumberger for offering license of ECLIPSE 2008.1 & tribute to all the scientists and researchers who have a capability of "seeing underground" and have made significant contribution in understanding of petroleum reservoirs which are one of the nature's ubiquitous and diverse materials. As;

"There are worlds to see in the grain of sand".

An expression of gratitude to Dr. Obed-ur-Rehman Paracha & Dr. Saeed Khan Jadoon for their guidance and to my senior Mr. Bilal Amjad for his valuable suggestions and assistance.

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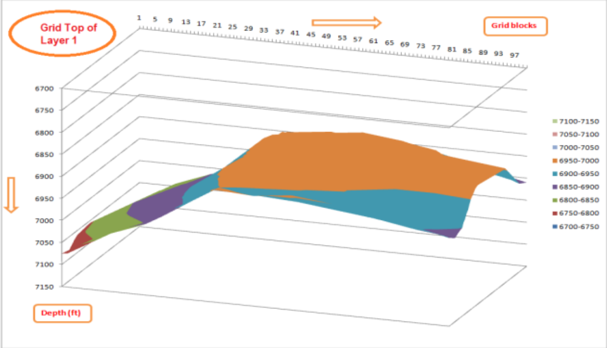

Figure 1: "Reservoir W" TOPS of First Layer

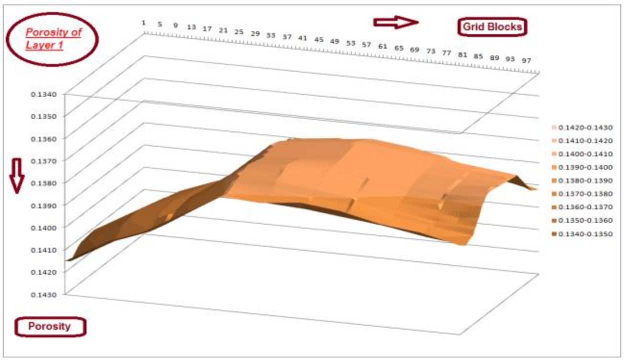

Figure 2: "Reservoir W" Porosity of First Layer

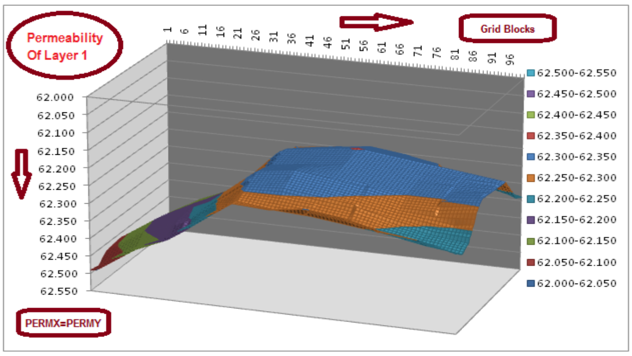

Figure 3: "Reservoir W" Permeability of First Layer:

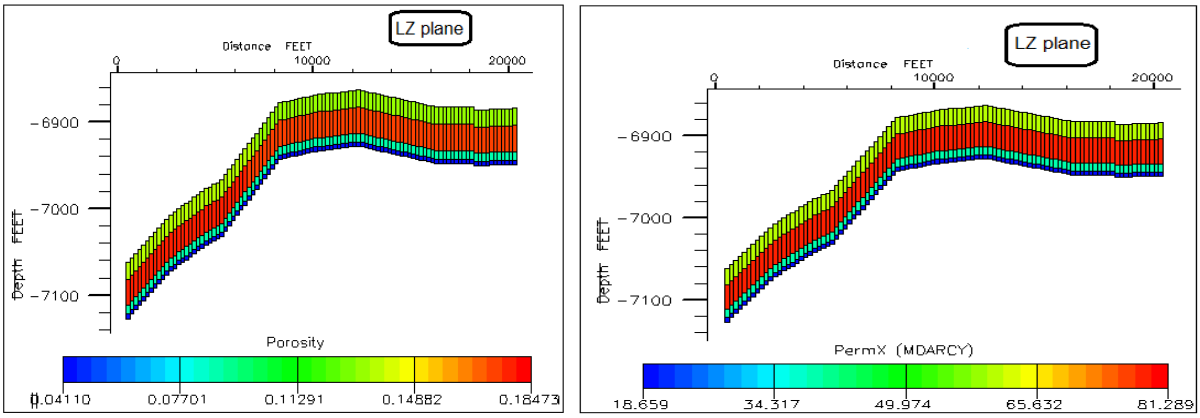

Figure 4: Porosity & PermX Variation of Individual Layers of "Reservoir W"

Gas Saturation Functions

S_g	K_{rg}	P_c (psia)
0	0	0
0.04	0	0.2
0.1	0.022	0.5
0.2	0.1	1
0.3	0.24	1.5
0.4	0.34	2
0.5	0.42	2.5
0.6	0.5	3
0.7	0.8125	3.5
0.78	1	3.9

Table 2: Gas Saturation Functions

Water Saturstion Functions

S_w	K_{rw}	Pc (psia)
0.22	0	7
0.3	0.07	4
0.4	0.15	3
0.5	0.24	2.5
0.6	0.33	2
0.8	0.65	1
0.9	0.83	0.5
1	1	0

Table 3: Water Saturation Functions

Oil Saturation Functions (3-phase)

S_o	K_{row}	K_{rowg}
0	0	0
0.2	0	0
0.38	0.00432	0
0.4	0.0048	0.004
0.48	0.05288	0.02
0.5	0.0649	0.036
0.58	0.11298	0.1
0.6	0.125	0.146
0.68	0.345	0.33
0.7	0.4	0.42
0.74	0.7	0.6
0.78	1	1

Table 4: Oil Saturation Functions

Gas-Oil PVT Properties					
	Gas PVT Properties		Oil PVT Properties		
Pressure (psia)	FVF (rb/MSCF)	Viscosity (cp)	R_s (MSCF/STB)	FVF (rb/STB)	Viscosity (cp)
34.69	565.332	0.0139382	0.00677059	1.09166	0.535935
208.69	92.9398	0.0140424	0.0348018	1.10388	0.521904
382.69	50.1478	0.0141957	0.0679715	1.11857	0.50474
556.69	34.1331	0.0143848	0.104259	1.13489	0.48573
730.69	25.7685	0.0146053	0.14287	1.15253	0.465656
904.69	20.6413	0.0148546	0.18336	1.17131	0.445112
1078.69	17.1862	0.0151311	0.22544	1.1911	0.424557
1252.69	14.7073	0.0154334	0.268904	1.21184	0.404335
1426.69	12.848	0.0157603	0.313602	1.23344	0.384701
1600.69	11.4066	0.0161104	0.359412	1.25586	0.365834
1774.69	10.2604	0.0164822	0.406238	1.27905	0.347855
1948.69	9.33037	0.0168742	0.45	1.30052	0.332575
2122.69	8.56318	0.0172846	---	1.29571	0.336858
2296.69	7.92159	0.0177117	---	1.29165	0.341142
2470.69	7.37875	0.0181536	---	1.28817	0.345425
2644.69	6.91481	0.0186086	---	1.28516	0.349708
2818.69	6.51477	0.0190748	---	1.28252	0.353992
2992.69	6.16709	0.0195506	---	1.28019	0.358275
3166.69	5.86275	0.0200344	---	1.27813	0.362559
3340.69	5.59462	0.0205247	---	1.27628	0.366842
3514.69	5.35697	0.0210201	---	1.27461	0.371125

Table 5: Gas-Oil PVT Properties

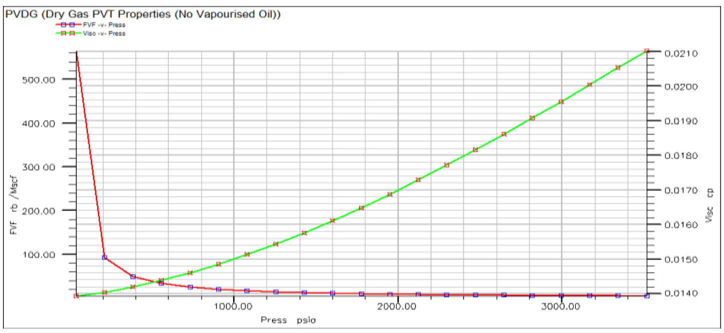

Figure 5: Dry Gas PVT Properties

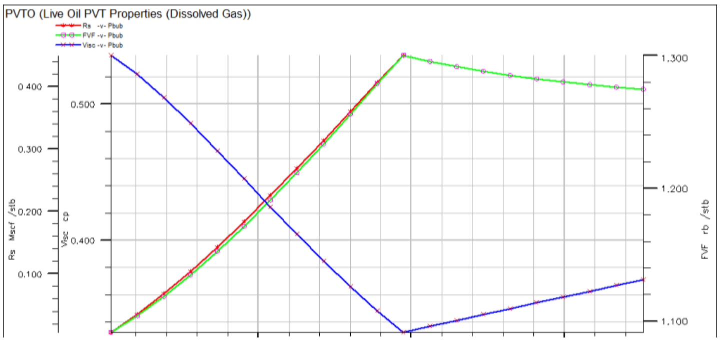

Figure 6: Live Oil PVT Properties

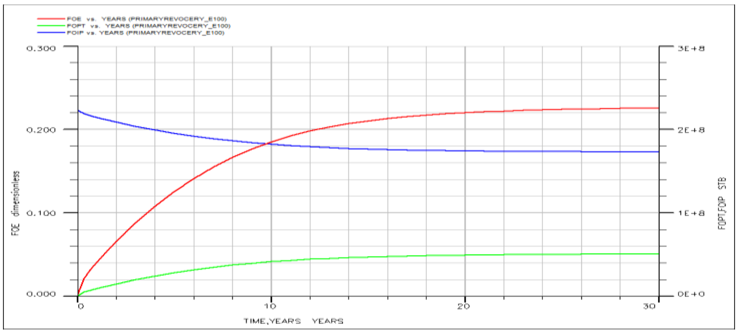

Figure 7: Performance of "Reservoir W" During Primary Recovery

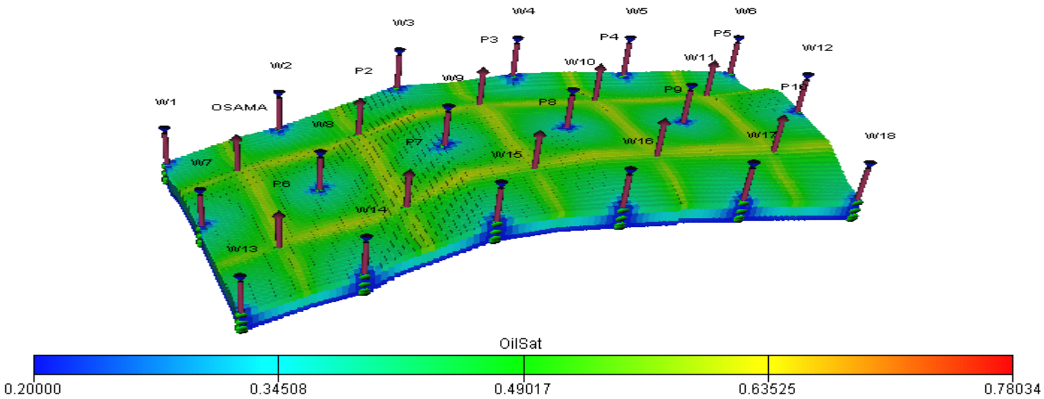

Figure 8: Five Spot 3D View Depicting Oil Saturation at end of Simulation

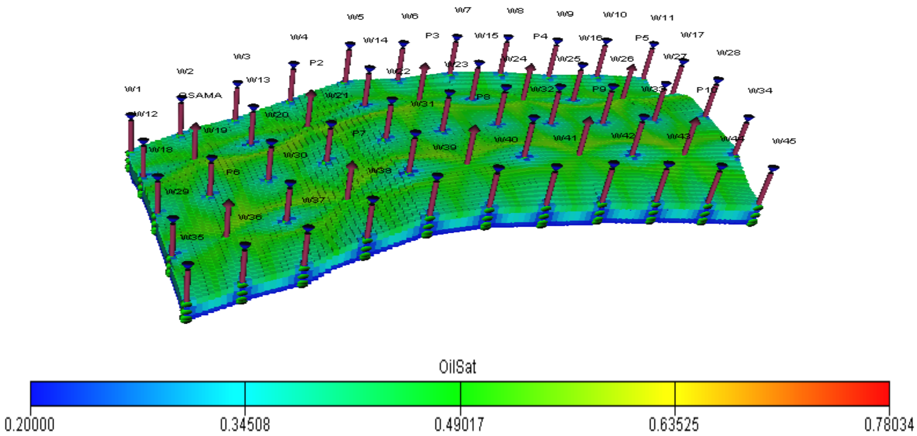

Figure 9: Nine Spot 3D View Depicting Oil Saturation at end of Simulation

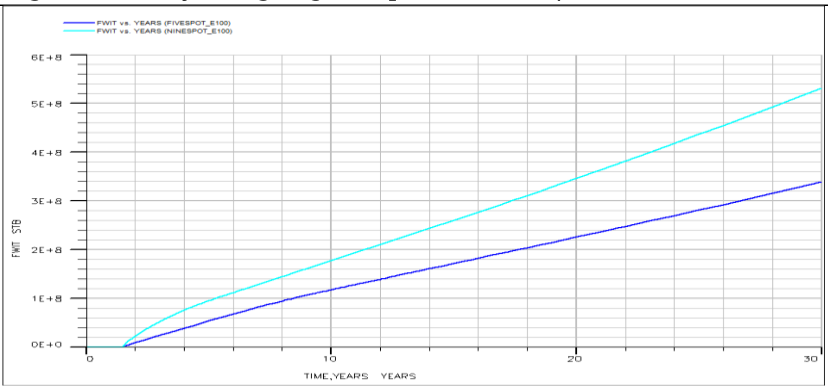

Figure 10: Five & Nine Spot Cumulative Water Injected

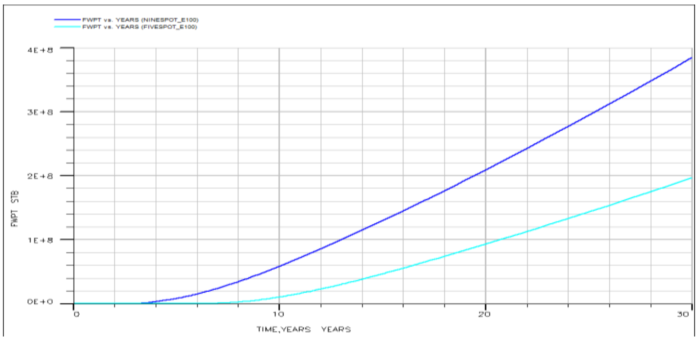

Figure 11: Five & Nine Spot Cumulative Water Produced

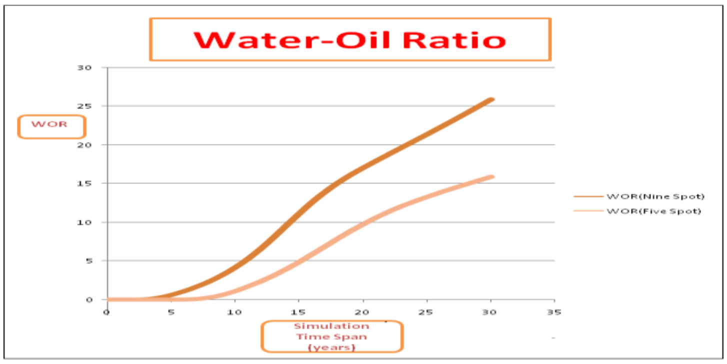

Figure 12: Five & Nine Spot WOR

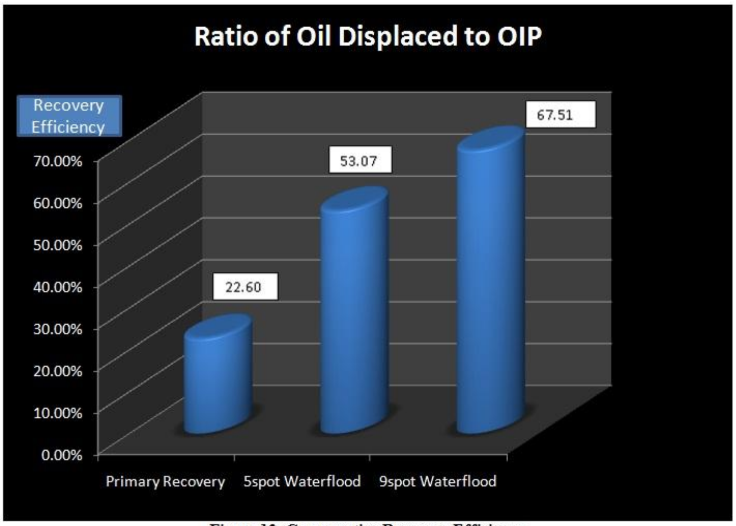

Figure 13: Comparative Recovery Efficiency

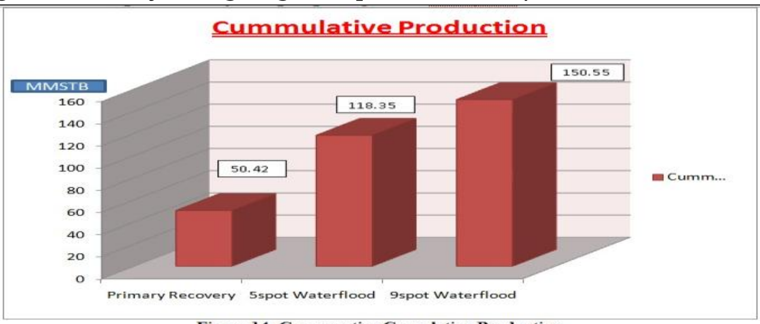

Figure 14: Comparative Cumulative Production

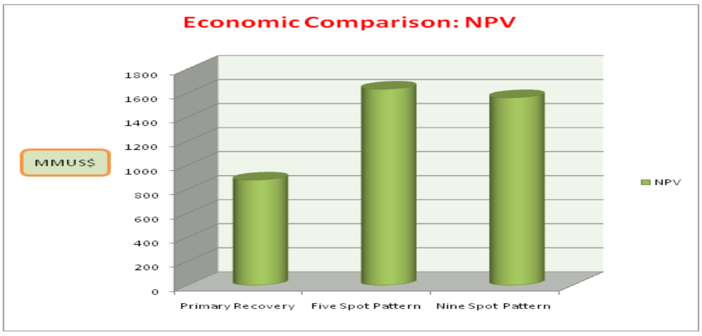

Figure 15: Net Present Value of Investment Opportunities

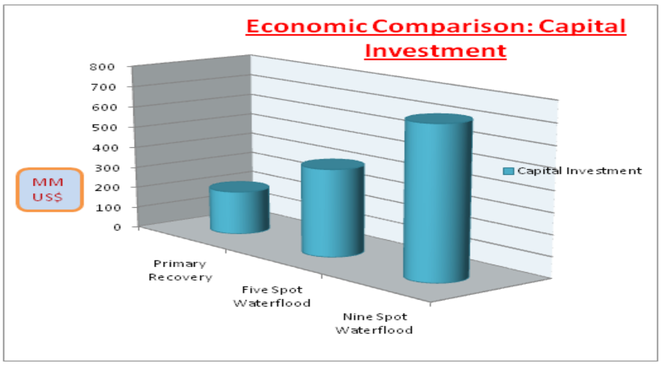

Figure 16: Capital Investment for Investment Opportunities

Economic Calculations: Base Case (Primary Recovery)									
Time Period		Production		Revenues			Expenses		
Year	Time step	Cumulative Production (MMSTB)	Periodic Production (MMSTB)	Revenue MM (US$)	Royalty MM (US$)	W.I Revenue MM (US$)	State Taxes (MM) (US$)	Operating Cost[MM US$]	Overhead MM US $
2011	0	0	---	0	0	0	0	0	0
2012	1	9.112397	9.112397	820.11	164.02	656.09	78.73	91.12397	27.337191
2013	2	14.71215	5.599751	503.97	100.79	403.18	48.38	55.99751	16.799253
2015	4	24.10456	4.437654	399.38	79.87	319.51	38.34	44.37654	13.312962
2017	6	31.50287	3.478742	313.08	62.61	250.46	30.05	34.78742	10.436226
2019	8	37.15996	2.62164	235.94	47.18	188.75	22.65	26.2164	7.86492
2021	10	41.33776	1.919564	172.76	34.55	138.20	16.58	19.19564	5.758692

2023	12	44.28119	1.334356	120.09	24.01	96.07	11.52	13.34356	4.003068
2025	14	46.28373	0.903284	81.29	16.25	65.03	7.80	9.03284	2.709852
2027	16	47.63676	0.610688	54.96	10.99	43.96	5.27	6.10688	1.832064
2031	20	49.19995	0.29066	26.15	5.23	20.92	2.51	2.9066	0.87198
2035	24	49.95673	0.141568	12.74	2.54	10.19	1.22	1.41568	0.424704
2039	28	50.3217	0.06718	6.04	1.20	4.83	0.58	0.6718	0.20154
2041	30	50.42097	0.044364	3.99	0.79	3.19	0.38	0.44364	0.133092
			50.42	**4537.88**	**907.57**	**3630.30**	**435.63**	**504.20**	**151.26**

Table 10: Economic Calculations Primary Recovery

Economic Calculations: Base Case (Primary Recovery) [Cont'd]					
Time Period		**Cash Flow**			
Year	**Time step**	**Before Tax Net Cash Flow (MM US $)**	**After Tax Net Cash Flow (MM US $)**	**Discounted Cash flow (MM $ US)**	**Cumulative Cash Flow (MM $ US)**
2011	0	-210	-210	-210	-210
2012	1	458.9003129	321.230219	292.0274719	82.02747186
2013	2	282.0034604	197.4024223	163.1424977	245.1699696
2015	4	223.4802554	156.4361788	106.848015	483.2465872
2017	6	175.1894471	122.632613	69.222913	638.2637332
2019	8	132.0257904	92.41805328	43.11370392	736.2882722
2021	10	96.66924304	67.66847013	26.08912456	796.1386184
2023	12	67.19816816	47.03871771	14.98798509	831.0077699
2025	14	45.48938224	31.84256757	8.385143258	850.6176896
2027	16	30.75424768	21.52797338	4.685114241	861.5674471
2031	20	14.6376376	10.24634632	1.523054091	871.2781328
2035	24	7.12936448	4.990555136	0.506669095	874.4874088
2039	28	3.3831848	2.36822936	0.164220956	875.5454566
2041	30	2.23417104	1.563919728	0.089625977	875.7570938
		2329.200	**1567.440**	**NPV= 875.757**	

Table 11: Economic Calculations Primary Recovery

Economic Calculations: Augmented Case (Five Spot Waterflood)								
Time Period		**Production**		**Injection**		**Revenues**		
Year	**Time step**	**Cumulative Oil Production (MMSTB)**	**Periodic Production MMSTB**	**Cumulative Water Injection (STB)**	**Periodic Injection MMSTB**	**Revenue MMUS$**	**Royalty MMUS$**	**W.I Revenue MMUS$**
2011	0	0	0	0	0	0	0	0
2012	1	9.112397	9.112	0	0	820.115	164.023	656.092
2013	2	15.057491	5.945	8535735	8.535	535.058	107.011	428.046
2015	4	35.867292	11.523	38541484	14.562	1037.147	207.428	829.715
2019	8	78.193864	8.833	94293720	12.9	795.005	159.001	636.004
2021	10	90.285328	5.199	1.17E+08	11.149	467.983	93.596	374.386
2027	16	105.855	1.601	1.82E+08	10.783	144.163	28.832	115.331
2031	20	110.54658	0.985	2.25E+08	10.852	88.714	17.742	70.971

2035	24	113.9941	0.802	2.69E+08	11.184	72.187	14.437	57.749
2041	30	118.35616	0.683	3.38E+08	11.716	61.546	12.309	49.237
			118.356		**338.448**	**10652.054**	**2130.410**	**8521.643**

Table 12: Economic Calculations Five Spot Waterflood

Economic Calculations: Augmented Case (Five Spot Waterflood) [Cont'd]								
Time Period		Expenses					Undiscounted Cash Flow	
Year	Time step	State Taxes MMUS$	Operating cost for Injection Water MM$	Operating Cost for Incremental Oil MM US$	Total Operating Cost MM$	Overhead MMUS$	Before Tax Cash Flow MMUS$	After Tax Cash Flow MMUS$
2011	0	0	0	0	0	0	-417	-417
2012	1	78.73111	0	91.12397	91.12397	27.33719	458.90	321.2302
2013	2	51.36561	17.07147	59.45094	76.52241	17.83528	282.32	197.6264
2015	4	99.56589	29.12481	115.2383	144.3631	34.57149	551.21	385.8507
2019	8	76.32051	25.80003	88.33392	114.134	26.50018	419.04	293.3347
2021	10	44.92641	22.29838	51.99816	74.29654	15.59945	239.56	167.695
2027	16	13.83972	21.56602	16.0182	37.58422	4.80546	59.10	41.37114
2031	20	8.516621	21.70468	9.8572	31.56188	2.95716	27.93	19.55533
2035	24	6.929971	22.36854	8.0208	30.38934	2.40624	18.02	12.61695
2041	30	5.908464	23.43276	6.8385	30.27126	2.05155	11.00	7.704148
		1022.597	**676.8967**	**1183.562**	**1860.458**	**355.0685**	**4866.52**	**3281.464**

Table 13: Economic Calculations Five Spot Waterflood

Economic Calculations: Augmented Case (Five Spot Waterflood) [Cont'd]			
Time Period		Discounted Cash Flow	
Year	Time step	Discounted Cash flow MM$US	Cumulative Cash Flow MM $ US
2011	0	-417	-417
2012	1	292.0275	-124.97253
2013	2	163.3276	38.355096
2015	4	263.5412	531.59456
2019	8	136.8428	1305.5198
2021	10	64.6537	1466.1042
2027	16	9.003566	1602.3017
2031	20	2.906775	1620.7565
2035	24	1.280943	1627.8899
2041	30	0.441514	1632.1955
		NPV=1632.196	

Table 14: Economic Calculations Five Spot Waterflood

Economic Calculations: Augmented Case (Nine Spot Waterflood)								
Time Period		Production		Injection		Revenues		
Year	Time step	Cumulative Oil Production (MMSTB)	Periodic Production MMSTB	Cumulative Water Injection (STB)	Periodic Injection MMSTB	Revenue MMUS$	Royalty MMUS$	W.I Revenue MMUS$
2011	0	0	0	0	0	0	0	0
2012	1	9.686647	9.686647	0	0	871.79823	174.35965	697.43858
2013	2	20.704032	11.01739	21.849876	21.849876	991.56465	198.31293	793.25172
2014	3	44.309528	23.6055	52.11548	30.265604	2124.4946	424.89893	1699.5957
2019	8	90.591592	4.76876	1.44E+02	16.36763	429.1884	85.83768	343.35072

2021	10	97.797408	3.199112	1.77E+02	16.4766	287.92008	57.584016	230.33606
2027	16	108.26086	1.21308	2.77E+02	16.80898	109.1772	21.83544	87.34176
2031	20	112.43228	0.9625	3.46E+02	17.60519	86.625	17.325	69.3
2035	24	115.9649	0.84124	4.18E+02	18.31398	75.7116	15.14232	60.56928
2039	28	119.0932	0.74886	4.93E+02	18.9473	67.3974	13.47948	53.91792
2041	30	120.53038	0.7088	5.31E+02	19.24221	63.792	12.7584	51.0336
			120.5304		**530.93235**	**10847.734**	**2169.5468**	**8678.1874**

Table 16: Economic Calculations Nine Spot Waterflood

Economic Calculations: Augmented Case (Nine Spot Waterflood) [Cont'd]								
Time Period		Expenses					Undiscounted Cash Flow	
Year	Time step	State Taxes MMUS$	Operating cost for Injection Water MM$	Operating Cost for Incremental Oil MM US$	Total Operating Cost MM$	Overhead MMUS$	Before Tax Cash Flow MMUS$	After Tax Cash Flow MMUS$
2011	0	0	0	0	0	0	-713	-713
2012	1	83.69263	0	96.86647	96.86647	29.05994	487.8195	341.4737
2013	2	95.19021	43.69975	110.1739	153.8736	33.05216	511.1358	357.795
2014	3	203.9515	60.53121	236.055	296.5862	70.81649	1128.242	789.7691
2019	8	41.20209	32.73526	47.6876	80.42286	14.30628	207.4195	145.1936
2021	10	27.64033	32.9532	31.99112	64.94432	9.597336	128.1541	89.70786
2027	16	10.48101	33.61796	12.1308	45.74876	3.63924	27.47275	19.23092
2031	20	8.316	35.21038	9.625	44.83538	2.8875	13.26112	9.282784
2035	24	7.268314	36.62796	8.4124	45.04036	2.52372	5.736886	4.01582
2039	28	6.47015	37.8946	7.4886	45.3832	2.24658	-0.18201	-0.12741
2041	30	6.124032	38.48442	7.088	45.57242	2.1264	-2.78925	-1.95248
		1041.382	**1061.865**	**1205.304**	**2267.169**	**361.5911**	**4295.045**	**2792.632**

Table 17: Economic Calculations Nine Spot Waterflood

Economic Calculations: Augmented Case (Nine Spot Waterflood) [Cont'd]			
Time Period		Discounted Cash Flow	
Year	Time step	Discounted Cash flow MM$US	Cumulative Cash Flow MM $ US
2011	0	-713	-713
2012	1	310.4306	-402.569
2013	2	295.6984	-106.871
2014	3	593.3652	486.4942
2019	8	67.73391	1395.684
2021	10	34.58626	1480.413
2027	16	4.185209	1549.019
2031	20	1.379827	1557.896
2035	24	0.407709	1560.725
2039	28	-0.00883	1561.205
2041	30	-0.11189	1561.026
		NPV=1561.026	

Table 18: Economic Calculations Nine Spot Waterflood