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EVALUATION OF OIL RECOVERY AND ECONOMICS OF WATERFLOODING IN NIGERIA

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Abstract

Waterflooding helps in the recovery of great amount of oil that would have otherwise been abandoned in the reservoir that is depleted. A reservoir in the Niger Delta, Reservoir OB-63 has been used to illustrate this. Reservoir OB-63 had oil initially in place as 9.6346 MMSTB and was produced for some time with the reservoir natural energy. The remaining oil in the reservoir as at the time that the natural energy of the reservoir was no more sufficient to produce oil was 3.88MMSTB. The reservoir has been left as depleted reservoir with the remaining oil in it. But from the analysis conducted in this work it is seen that if secondary oil recovery project by waterflooding is embarked on the reservoir, part of the remaining abandoned oil would be recovered. With the specifications given, about 1.59MMSTB of the 3.88MMSTB of oil in reservoir OB-63 would be produced as at the breakthrough time of 760 days. Moreover, considering the economic aspect of the project, reservoir OB-63 and is good to be invested in. From the NPV calculations performed, it is seen that the NPV of reservoir OB-63 at discount rate of 10% is $5.30 million. Since the NPV at the time of breakthrough is greater than zero, it is worth investing in.

Keywords: waterflooding; secondary oil recovery; factor, production; injection; water; fractional flow; efficiency; displacement; areal sweep; vertical sweep.

1. Introduction

1.1 Background information

According to Tharek [7] enhanced oil recovery (EOR) is "the recovery of oil by injection of a fluid that may or may not be native to the reservoir." EOR is a means to extend the productive life of an otherwise depleted and uneconomic oil field. It is usually practiced after recovery by other, less risky and more conventional methods, such as pressure depletion and water flooding.

Not all reservoirs are amenable to EOR. Effective screening practices must be employed to identify suitable candidates. As part of the screening, discounted cash-flow projections are routinely performed to assess profitability. At the core of these projections is an estimate of recovery performance.

All of currently available EOR is based on one or more of two principles: increasing the capillary number and/or lowering the mobility ratio, compared to their waterflood values. Increasing the capillary number means, practically speaking, reducing oil-water interfacial tension. The injectant mobility may be reduced by increasing water viscosity, reducing oil viscosity, reducing water permeability or all of the above.

Movement of reservoir fluids to the surface through the wellbore requires physical driving phenomena. Early in the producing life of a well, the driving force is natural resulting from any or the combination of:

- the expansion of gases dissolved in the oil, if the pressure is below bubble point (solution gas drive),
- the expansion of the gas cap (gas cap drive),
- the expansion of an aquifer under the accumulation (natural water drive),

- the single-phase expansions of the reservoir rock and of the fluids: gas, under-saturated oil or water accompanying a pressure drop (compaction drive).

But as production continues, this primary energy becomes depleted with consequent pressure reduction and approaches a limit where further production by the primary recovery methods becomes uneconomical and insufficient. Except in the case of gases or of the presence of an active aquifer (fed from the exterior), the natural recovery rates obtained are low (20 to 25 %). Ultimately, natural energy must be supplemented to improve recovery from the reservoir. Supplementary energy can be achieved either through artificial lift, or fluid injection process. Artificial lift has major disadvantages in terms of recovery if the reservoir is allowed to become depleted.

Fluid Injection into the reservoir allows the pressure to be maintained. It is done by injecting water or gas into the reservoir via one wellbore and production of oil and/or gas from another wellbore. By far, the most common fluid injected is water because of its availability, low cost and high specific gravity which facilitates injection. By injecting the water into the producing formation a process otherwise called Water Flood, well pressure and product flow is maintained by displacing the produced oil. Water injection yields about 80-85% of additional oil produced.

1.2 Primary reservoir drive mechanisms

Six driving mechanisms basically provide the natural energy necessary for oil recovery. These driving mechanisms are presented in Table 1.1 with their oil recovery ranges. The recovery of oil by any of the above driving mechanisms is called primary recovery. The term refers to the production of hydrocarbons from a reservoir without the use of any process (such as water injection) to supplement the natural energy of the reservoir. The primary drive mechanism and anticipated ultimate oil recovery should be considered when reviewing possible waterflood prospects. The approximate oil recovery range is tabulated below for various driving mechanisms. Note that these calculations are approximate and, therefore, oil recovery may fall outside these ranges.

Table 1.1 Approximate recovery range in reservoir with various drive mechanisms

Driving Mechanism	Oil Recovery Range %
Rock and liquid expansion	3–7
Solution gap	5–30
Gas cap	20–40
Water drive	35–75
Gravity drainage	<80
Combination drive	30–60

Source: Tharek [7]

Generally, for oil to flow the primary drive mechanisms help to drive the oil to the surface. Soon the initial pressure of the reservoir drops below economic limits after the reservoir recovers at least 40% of the oil in place. Enhanced oil recovery helps to recover the remaining 60% locked in the subsurface. Below is a figure illustrating the different methods of enhanced oil recovery.

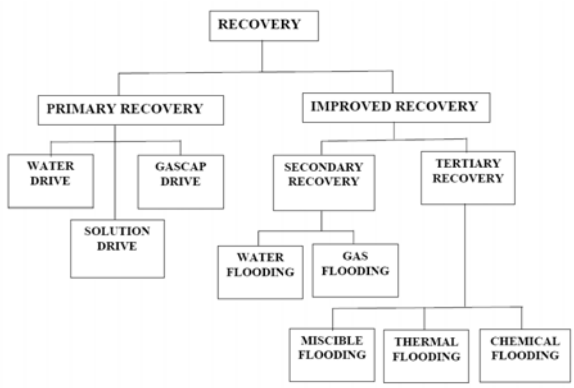

Fig 1.1 Different Methods of Oil Recovery

2. Theory

2.1 Oil recovery analysis

2.1.1 Calculation of Overall Recovery Efficiency

The overall recovery factor (efficiency) RF of any secondary or tertiary oil recovery method is the product of a combination of three individual efficiency factors as given by the following generalized expression:

$$RF = E_D E_A E_V \quad (2.1)$$

Cumulative oil production, N_P can be expressed as:

$$N_P = N_S E_D E_A E_V \quad (2.2)$$

where, RF = overall recovery factor; N_S = initial oil in place at the start of the flood, STB; N_P = cumulative oil produced, STB; E_D = displacement efficiency; E_A = areal sweep efficiency; E_V = vertical sweep efficiency.

The displacement efficiency E_D is the fraction of movable oil that has been displaced from the swept zone at any given time or pore volume injected. Because an immiscible gas injection or waterflood will always leave behind some residual oil, E_D will always be less than 1.0.

The areal sweep efficiency E_A is the fractional area of the pattern that is swept by the displacing fluid.

2.1.2 Oil Recovery Calculations

Oil produced, N_p before or after breakthrough = $NsE_D E_A E_V$ When initial gas saturation,

$$S_{gi} = 0,\ E_D = (\bar{S}_w - S_{wi})/(1 - S_{wi}) \quad (2.3)$$

At breakthrough,

$$ED_{BT} = (\bar{S}_{wBT} - S_{wi})/(1 - S_{wi}) \quad (2.4)$$

$$(N_p)_{BT} = N_s E_{DBT} E_{ABT} E_{VBT} \quad (2.5)$$

Assuming E_A and E_V are 100%

$$(N_p)_{BT} = N_s E_{DBT} \quad (2.6)$$

Before breakthrough, S_{gi} = 0, water production, W_p = 0 and flow rate of water, Q_w = 0 After breakthrough, S_{gi} = 0, E_A, E_V = 100%

2.1.3 Calculation of Displacement Efficiency

Mathematically, the displacement efficiency is expressed as:
E_D = (Volume of oil at start of flood – Remaining oil volume)/ Volume of oil at start of flood

$$E_D = [(PV)(S_{oi}/B_{oi}) - (PV)\bar{S}_o(\bar{S}_o/B_o)]/[(PV)(S_{oi}/B_{oi})] \quad (2.7)$$

$$E_D = [(S_{oi}/B_{oi}) - (\bar{S}_o/B_o)]/(S_{oi}/B_{oi}) \quad (2.8)$$

where S_{oi} = initial oil saturation at start of flood; B_{oi} = oil formation volume factor at start of flood, bbl/STB; S_o = average oil saturation in the flood pattern at a particular point during the flood.

At a constant oil FVF,

$$E_D = (S_{oi} - \bar{S}_o)/S_{oi} \quad (2.9)$$

Initial oil saturation,

$$S_{oi} = 1 - S_{wi} - S_{gi} \quad (2.10)$$

In the swept area, gas saturation is considered zero,

$$\bar{S}_o = 1 - \bar{S}_w \quad (2.11)$$

Substituting in eqn 2.9,

$E_D = (S_w - S_{wi} - S_{gi})/(1 - S_{wi} - S_{gi})$

$\bar{S}_w$= average water saturation in the swept area ; S_{gi} = initial gas saturation at the start of flood; S_{wi} = initial water saturation at the start of flood ; if no initial gas is present at the start of flood.

$$E_D = (\bar{S}_w - S_{wi})/(1 - S_{wi}) \quad (2.12)$$

As $\bar{S}_w$ increases at different stages of the flood E_D also increases until it reaches maximum when the average oil saturation in the area of the flood pattern is reduced to the residual oil saturation S_{or} or equivalently when $S_w = 1 - S_{or}$

E_D will continually increase with increasing water saturation in the reservoir. The problem, of course, lies with developing an approach for determining the increase in the average water saturation in the swept area as a function of cumulative water injected (or injection time). Buckley and Leverett [1] developed the fractional flow equation which provides the basis for establishing such a relationship.

2.1.3.1 Fractional Flow Equation

The fractional flow equation is a model used to determine the water fraction of the total fluid flow at a particular location and time in a linear reservoir waterflood.

This model provides insight into the immiscible waterflood displacement process and the relative effects of different rock, fluid, and operational properties on displacement efficiency. The location and time for a fractional flow value are obtained by determining the saturation history for that location.

The development of the fractional flow equation is attributed to Leverett [1]. For two immiscible fluids, oil and water, the fractional flow of water, fw is given by the equation:

$$F_w = \frac{1 + \dfrac{1.127 * 10^{-3} A\, K_o\, [\partial P_c/\partial L - 0.433\ \Delta\delta \sin\alpha]}{q_t\, \mu_o}}{1 + \mu_w K_o/(K_w\, \mu_o)} \quad (2.13)$$

q_o = Oil flow rate, RB/day; q_w = Water flow rate, RB/day; K_o = Effective permeability to oil, mD; K_w = Effective permeability to water, mD; A = Cross sectional area to flow, sq ft ;μ_o = Oil viscosity, cp ; μ_w = Water viscosity, cp; P_c = Capillary pressure ;γ= Specific gravity of the fluids, fraction; α= Angle of inclination, positive up dip, degrees

In the case of a water drive, neglecting the effects of the capillary pressure gradient and dip of the reservoir, the terms $\partial P_c/\partial L$ and $0.433\Delta\gamma \sin \alpha$

Fractional flow rate of water which is the displacing fluid is defined as the water flow rate divided by the total flow rate, or:

$$F_w = q_w/q_t = q_w/(q_o + q_w) \quad (2.14)$$

where F_w = fraction of water in the flowing stream, i.e., water cut, bbl/bbl

$$q_t = \text{total flow rate, bbl/day} = q_o + q_w \quad (2.15)$$

q_w = water flow rate, bbl/day; q_o = oil flow rate, bbl/day

2.1.4 Areal Sweep Efficiency

The areal sweep efficiency E_A is defined as the fraction of the total flood pattern that is contacted by the displacing fluid. It increases steadily with injection from zero at the start of the flood until breakthrough occurs, after which E_A continues to increase at a slower rate. The areal sweep efficiency depends basically on the following three main factors:

1. Mobility ratio, M
2. Flood pattern
3. Cumulative water injected W_{inj}

2.1.4.1 Mobility ratio

The mobility ratio M is defined as the mobility of the displacing fluid to the mobility of the displaced fluid.

Mobility of oil = $K_o/\mu_o = KK_{ro}/\mu_o$ (2.16)

Mobility of water = $K_w/\mu_w = KK_{rw}/\mu_w$ (2.17)

Mobility ratio = mobility of displacing fluid/mobility of displaced fluid $=(K_w/\mu_w)/(K_o/\mu_o)$ (2.18

2.1.4.2 Areal Sweep Prediction Methods

Methods of predicting the areal sweep efficiency are essentially divided into the following three phases of the flood:

- Before breakthrough
- At breakthrough
- After breakthrough

Phase 1: Areal Sweep Efficiency Before Breakthrough

The areal sweep efficiency before breakthrough is simply proportional to the volume of water injected and is given by:

Before breakthrough,

$E_A = W_{inj}/[(PV)(S_{wBT} - S_{wi})]$ (2.19)

where W_{inj} = cumulative water injected, bbl; (PV) = flood pattern pore volume, bbl.

Phase 2: Areal Sweep Efficiency at Breakthrough

Craig [2] proposed a graphical relationship that correlates the areal sweep efficiency at breakthrough E_{ABT} with the mobility ratio for the five spot pattern. The graphical illustration of areal sweep efficiency as a strong function of mobility ratio shows that a change in the mobility ratio from 0.15 to 10.0 would change the breakthrough areal sweep efficiency from 100 to 50%. Willhite [8] presented the following mathematical correlation,

$E_{ABT} = 0.54602036 + 0.03170817/M + 0.30222997/e^M - 0.00509693M$ (2.20)

where, E_{ABT} = areal sweep efficiency at breakthrough; M= mobility ratio

Phase 3: Areal Sweep Efficiency After Breakthrough

In the same way that displacement efficiency E_D increases after breakthrough, the areal sweep efficiency also increases due to the gradual increase in the total swept area with continuous injection. Dyes *et al.* [3] correlated the increase in the areal sweep efficiency after breakthrough with the ratio of water volume injected at any time after breakthrough, W_{inj}, to water volume injected at breakthrough, W_{iBT}, as given by:

$E_A = E_{ABT} + 0.633\log(W_{inj}/Wi_{BT})$ (2.21)

2.1.5 Vertical Sweep Efficiency

The vertical sweep efficiency, E_V, is defined as the fraction of the vertical section of the pay zone that is the injection fluid. This particular sweep efficiency depends primarily on (1) the mobility ratio and (2) total volume injected. As a consequence of the non-uniform permeabilities, any injected fluid will tend to move through the reservoir with an irregular front. In the more permeable portions, the injected water will travel more rapidly than in the less permeable zone. Perhaps the area of the greatest uncertainty in designing a waterflood is the quantitative knowledge of the permeability variation within the reservoir. The degree of permeability variation is considered by far the most significant parameter influencing the vertical sweep efficiency.

2.2 Waterflood process installation and development

2.2.1 Drilling of Water Injection and Production wells

Once water source has been confirmed and certified fit for use according to engineering standards for waterflooding, the water injection well is drilled into the aquifer near the oil reservoir through which water can be injected into the reservoir to displace the oil in the reservoir and the oil production wells also drilled. Note that these wells are drilled to patterns.

2.2.2 Design of Waterflood Plants

The next on the list is the installation of waterflooding plants or pumps. Waterflooding pumps are meant for the injection of the water into the reservoir and the waterflooding pumps or plant is located just close to the water injection well on site.

The selection and the sizing of waterflood plant facilities normally are unique to each water-flood because of the many variable parameters. The primary parameters might be the volume and pressure, while secondary parameters might include the treating requirements and the economic position of the investor. A variation in any single one of these parameters might drastically modify or completely change the selection and sizing of a waterflood plant. The volumes of injection water to be handled will of course be the most important basic item of information to learn for determining the size of the plant. Here, too, there are several parameters on which the calculation is based. Essentially, the water volume is a function of the gross size of the reservoir to be flooded, the porosity of the reservoir rock, the anticipated conformity or efficiency of the flood, and the ROS at both the initiation and completion of the flood. These data will be applied to the actual reservoir calculations, and only the final gross volume and the required daily injection rate must be known by the plant designer.

Water lines are also installed to transmit water from the water well or water source to the waterflooding pumps on site.

3. Results

3.1 Oil recovery calculation for reservoir OB-63

Reservoir OB-63 located at Niger Delta is under consideration for waterflooding. The relative permeability data and the corresponding water cut are given in table A.1 in the appendix. Also the reservoir and fluid data for the solution drive reservoir is given in table A.2 in the appendix. The Proposed Waterflood data for the project is in table A.3 in the appendix. The recovery performance is to be predicted with the given data at a constant water injection rate.

Phase 1: Initial Calculations

Step 1: Pore Volume and Volume of oil at start of flood

PV = 7758 * Flood Area * Formation thickness * Porosity = 7758 * 45 acres * 80 ft * 0.25 = $6.98 * 10^6$ bbl

Volume of oil at start of flood, Ns

Ns = $PV(1 - S_{wc})/B_o$ = [$6.98 * 10^6$ bbl * (1 – 0.20)]/1.438 = 3.88 MMSTB

Step 2: Plot f_w vs S_w on a Cartesian scale and determine $S_{wf} = S_{wBT} = 0.58$

and $f_{wf} = f_{wBT} = 0.88$

$\bar{S}_{wBT} = 0.667$

$f_{wBT} = 1.0$

Step 3: Determine K_{ro} at S_{wi} and K_{rw} at $\bar{S}_{wBT}$ from the relative permeability data:

K_{ro} *at* S_{wi}, 0.20 = 0.9

K_{rw} at $\bar{S}_{wBT}$, 0.667 = 0.415

Step 4: Mobility ratio, M

$M = K_{rw}\mu_o/K_{ro}\mu_w$

M = (0.415 * 1.0)/(0.9 * 0.5)

M = 0.923

Step 5: Areal Sweep Efficiency at breakthrough, E_{ABT}

$E_{ABT} = 0.54602036 + 0.03170817/M + 0.30222997/e^M - 0.00509693M$

$E_{ABT} = 0.70$

Phase 2: Calculation of Recovery Performance to breakthrough

Step 1: Cumulative pore volumes of water injected at breakthrough, Q_{iBT}

$Q_{iBT} = \bar{S}_{wBT} - S_{wi}$ = 0.667 – 0.20= 0.467

Step 2: Cumulative water injected at breakthrough, W_{iBT}

W_{iBT} = (PV) Q_{iBT} E_{ABT}= 6.98 * 10^6 bbl * 0.467 * 0.70= 2.28 MM bbl

Step 3: Time to break through, t_{BT}

$t_{BT} = W_{iBT} / i_w$

i_w = injection rate = 3000 bbl/day

t_{BT} = 2.28 MM bbl / 3000 bbl/day

t_{BT} = 760 days

Step 4: Displacement efficiency at breakthrough, E_{DBT}

$E_{DBT} = [\bar{S}_{wBT} - S_{wi}] / (1 - S_{wi})$ = [0.667 – 0.20] / (1 – 0.20) = 0.5838

Step 5: Cumulative oil production at breakthrough, $[N_p]_{BT}$

$[N_p]_{BT} = N_s E_{DBT} E_{ABT}$ = 3.88 * 10^6 bbl * 0.5838 * 0.70= 1.59 MM STB

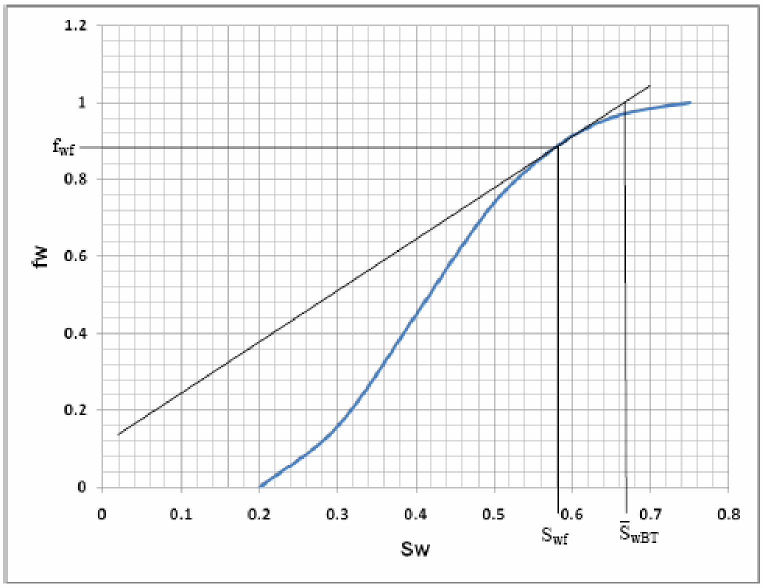

Fig 3.1 Graph of f_w against S_w of Reservoir OB-63

3.1.1Recovery Analysis for Reservoir OB-63

Table 3.1 Oil Recovery Calculation Data for the Waterflooding Project of Reservoir OB-63

Water viscosity,	0.5 cp
Proposed Flood area, A	45 acres
Proposed Flood pattern	5 spot
Proposed Water Injection Rate	3000 bbl/day
Pore Volume at start of flood	6.98 * 10^6 bbl
Volume of oil at start of flood, N_s	3.88 MMSTB
Mobility ratio, M	0.923
Areal Sweep Efficiency at breakthrough, E_{ABT}	0.70
Cumulative PV of water injected at breakthrough, Q_{iBT}	0.467
Cumulative water injected at breakthrough, W_{iBT}	2.28 MM bbl
Time to break through, t_{BT}	760 days
Displacement efficiency at breakthrough, E_{DBT}	0.5838
Cumulative oil production at breakthrough, $[N_p]_{BT}$	1.59 MM STB

From the table above the cumulative oil production at breakthrough which is about 760 days of waterflooding is 1.59 MM STB covering about 41% of the initial volume of oil at the start of flood which is good. The areal sweep efficiency at breakthrough and the displacement efficiency at breakthrough are 0.70 and 0.5838 respectively. Without the waterflooding project, as big as 1.59 MMSTB of oil would still be held in the formation.

In as much as the 41% of oil recovery is acceptable there are some parameters which could be varied to yield more oil. For instance the water that would be used for injection has a viscosity of 0.5cp, some surface active agents can be added to the water to increase the viscosity of the water which will in turn decrease the mobility ratio, increase the areal sweep efficiency and the cumulative oil production at breakthrough.

Here is a little illustration: assuming the water viscosity is increased with surface active agents to 0.65cp, the mobility ratio will reduce from 0.923 to 0.709, the areal sweep efficiency will change from 0.70 to 0.7358 and the cumulative oil production at breakthrough would be 2.23 MMSTB instead of 1.59 MMSTB.

2.23 MMSTB is about 43% of the initial volume of oil before waterflood. They are given in a table below:

Table 3.2 Effect of change in water viscosity for oil recovery from Reservoir OB-63

Parameter	Value at 0.5cp water viscosity	Value at 0.65cp water viscosity
Mobility ratio, M	0.923	0.709
Areal Sweep Efficiency at breakthrough, E_{ABT}	0.70	0.7358
Cumulative oil production at breakthrough, $[N_p]_{BT}$	1.59 MMSTB	2.23 MMSTB
$[N_p]_{BT}$ as % of N_s	41%	43%

3.2 Economic analysis of secondary oil recovery by waterflooding for reservoir OB-63

3.2.1 Investment costs

The costs mean whatever it takes for the installation of the project facilities and the operation of the facilities. Costs in this text comprise initial investment costs and the operating costs.

For instance, if a fivespot pattern is chosen as the waterflood pattern, it will cost some money to drill and complete the wells for injection and production.

Costs of the equipment used as injectors and water pumps or waterflooding plants as the case may be are also considered.

Costs of water and waterlines if the water source is away from the site or costs of drilling a water well if preferred is also put into consideration.

If the water needs treatment then water treatment costs will also be considered.

i For 5-spot pattern, the cost of drilling and completing water injection wells are given below:
- The cost of drilling and completing a well is $150 per foot
- For a total depth of 11 000 ft, the cost of drilling and completing the well is $150 * 11000 ft = $1.65 million
- The cost of installation of wellhead structures is $10000

Total cost of one well is $1.65 million + $10000 = $1.66 million

Therefore drilling cost of the 5 wells is $1.66 million * 5 = $8.3 million, (Philips, 2009).

ii The cost of installation of water injection pump for example an Elmar water/grease injection control module is $208 000

iii Costs of water and water lines for injection:
- The cost of drilling a water well to about 1500 ft is $2000, (Philips, 2009).
- The cost of installing a gathering system for the water gathering is $50 000.
- The cost of installing water lines for transporting the water from about 10 miles away from the oil well where the water well is, execution of associated civil works and maintenance of water facility for two years is less than $866 600, (Oil Serve Nigeria, Jan, 2004).

The total cost of water and water lines is $2000 + $50000 + $866 600 = $918600. The total investment cost is the sum of the costs of drilling the water injection wells, the cost of installing a water injection pump and the cost of water and water lines. The total investment cost is $8.3 million + $208 000 + $918 600 = $9.42 million

3.2.2 Operating costs

Operating cost = Labour costs + Maintenance costs + Management costs

Labour costs: take the number of employees to be 50 and an average of $4 000 per month per employee.

For the 50 of them, labour costs per month would be equal to 50 * $4 000 = $200 000. Then labour costs annually = $200 000 * 12 = $2.4 million

- Maintenance costs: these include spare parts consumption in amount of $2.13 million per year; fixed assets repair in amount of $852 000/year; operating outsourced services in amount of $4.26 million/year.

Total maintenance costs per year = $2.13 million + $852 000 + $4.26 million = $7.24 million.

- Management costs = $804 000

Annual Operating cost = $2.4 million + $7.24 million + $804 000= $10.44 million

3.2.3 Profitability Analysis of Reservoir OB-63

In profitability analysis of the reservoir OB-63, the gross revenue of the project is considered, the gross revenue of the project is gotten by finding the net value of the amount of oil recovered in the course of the project. The net value of the oil recovered is calculated using the market price of crude oil. In this work the price of crude oil is taken to be $30 per barrel. Then for reservoir OB-63 with cumulative oil production at breakthrough, $[Np]_{BT}$ of 760 days is 1.59MMSTB the net value of the oil is $30 * 1.59MMSTB = $47.7 million.

In this work, 1 year is assumed to contain 330 working days with the remaining days meant for equipment servicing and maintenance. For accurate economic evaluation of the project, it is assumed that the amount of oil recovered after 330 days is 690 395 STB

3.2.4 Net Present Value of Reservoir OB-63

Net Present Value, (NPV) is a measure of profitability of any project. The net present value of a time series of cash flows, both incoming and outgoing, is the sum of the present values (PVs) of the individual cash flows.NPV compares the value of 1 dollar today its value in future, taking inflation and returns into consideration. If the NPV of a prospective project is positive, it is accepted. However, if NPV is negative, the project should be discouraged because cash flows will also be negative, (Woodside Petroleum [9]).

Table 3.3 Cash Flows for the waterflooding project, Reservoir OB-63

Year	INV	REV	EXP	NCR	CUM. NCR	PV @ 10%
0	$9.42M	-	-	($9.42M)	($9.42M)	($9.42M)
1(330 days)	-	$20.7M	$10.44M	$10.26M	$0.84M	$9.33M
2(660 days)	-	$20.7M	$10.44M	$10.26M	$11.1M	$8.5M
Breakthrough (760 days)	-	$6.3M	$10.44M	($4.14M)	$6.96M	($3.11M)

From table 3.3, the Net Present Value at an expected rate of return/discount rate (the rate which the capital needed for the project could return if invested in an alternative venture) of 10% becomes;-$9.42M + $9.33M + $8.5M - $3.11M = $5.3million

The project is worth investing on since the NPV in the case is greater than zero.

3.2.5 The Net Present Values for the waterflooding project on reservoir OB-63 at variable prices of crude oil

Table 3.4 NPV at various crude oil prices, reservoir OB-63

Price of Crude Oil	NPV at the Crude Oil Price
$20/bbl	($8.28 M)
$30/bbl	$5.30 M
$40/bbl	$18.83 M
$50/bbl	$35.83 M

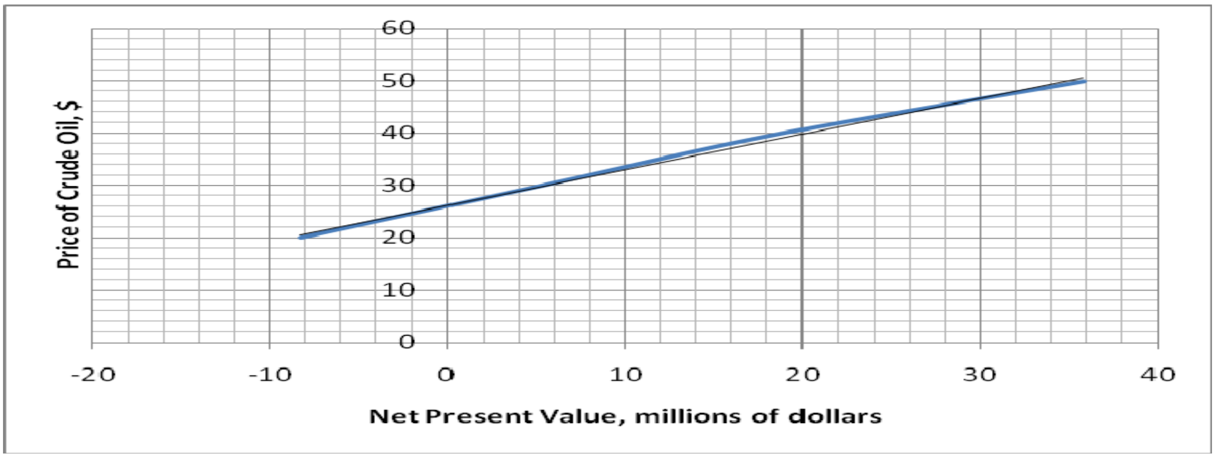

Fig 3.2 Plot of Price of Crude oil against the NPV's at the different prices, reservoir OB-63.

From the plot above it can be read that the NPV becomes negative as the price of crude oil drops below $26.

Therefore it is concluded that for embarking on waterflooding project on reservoir OB-63 to be economically viable, the price of crude oil would not fall below $26.

3.2.6 The Net Present Values for the waterflooding project on reservoir OB-63 at variable interest rates

Table 3.5 NPV at various interest rates at oil price of $30/bbl, reservoir OB-63

Interest rate	NPV at the interest rate
10%	$5.30 M
20%	$3.86 M
40%	$1.63 M
60%	($10 400)

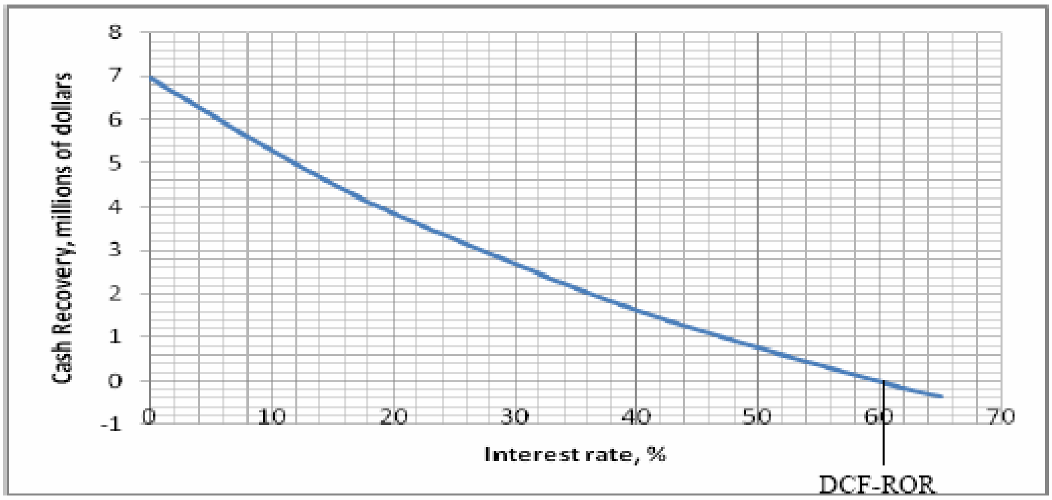

Fig 3.3 Plot of Cash Recovery against interest rates, reservoir OB-63

From the plot above it can be read that the DCF-ROR is 60%. Discounted Cash Flow- Rate of Return (DCF-ROR) is a profit indicator and it is that discount rate that discounts all future revenues to just equal all future costs. It discounts the Net Present Value of the project to zero.

4. Conclusion

Evaluation of reservoir OB-63 for waterflooding was performed in this research work. The results of the analyses were presented to show that such type of reservoir is suitable for waterflooding project, if properly managed, may be efficient from both technical and economic point of view.

Equations were used for estimation of the payoff capacities of the reservoirs, amount of water to be injected into the reservoir at given conditions initiating the sweep efficiencies. The profitability analyses were carried out to get the net present value to check the viability of investing in the projects.

The successful management of any waterflood project, especially in stratified/heterogeneous reservoirs, relies heavily on knowing what is going on in every well in the field. Once a waterflood is installed, proper operations are required to obtain the best results. Successful Waterflood is a more attractive alternative to abandonment of reservoir where applicable.

Nomenclature

a - distance between wells of the same type,
A - Cross sectional area to flow, sq ft
bbl - barrel
bbl/day - barrel per day
Bbl/acre-ft - barrel per acre foot
Bbl/ft - barrel per foot
B_{oi} - oil formation volume factor at start of flood, bbl/STB
B_{or} - the oil formation volume factor after water-flooding.
CUM NCR - cumulative net cash recovery
d - distance between lines of injectors and producers.
E_A - areal sweep efficiency
E_{ABT} - areal sweep efficiency at breakthrough
E_D - displacement efficiency
EOR - enhanced oil recovery
E_V - vertical sweep efficiency
EXP - expenses
ft - foot/feet
FVF - formation volume factor.
F_w - fractional water flow
gal/min-sq ft - gallon per minute square foot
in - inch
I - Initial investment
K_o - Effective permeability to oil, md
K_w - Effective permeability to water, md
k_{rw} - relative permeability to water at Sor
k_{ro} - relative permeability to oil at Swi
M- mobility ratio
M - Million
mD - milidarcy
m - metre
MMSTB - million stock tank barrel
n - number of days the project will last
NCR - net cash recovery
NPV - Net Present value
N_P - cumulative oil produced, STB
N_S - initial oil in place at the start of the flood, STB
NV - Net Value of the oil recovered, $
P_c - Capillary pressure
ppm - parts per million
Psi/ft - pounds per square inch per foot
PV - present value
PV - pore vol
P_{wf} - bottomhole flowing injection pressure
P_e - pressure at r_e distance from injection well
q_o - Oil flow rate, RB/day
q_w - Water flow rate, RB/day
q_t - total flow rate, bbl/day
r_e - external boundary radius
r_w - effective radius of a well
REV - revenue
RF - overall recovery factor
ROS - residual oil saturation
R_W is the outer radius of the waterflood front
R_e is the outer radius of the oil bank.
S_{gi} - initial gas saturation
S_{gt} - trapped gas saturation
$\underline{S}_{oi}$ - initial oil saturation at start of flood
$\overline{S}_o$ - average oil saturation in the flood pattern at a particular point during the flood
$\overline{S}_w$ - average water saturation in the swept area
S_{gi} - initial gas saturation at the start of flood
S_{wi} - initial water saturation at the start of flood
S_g - gas saturation
S_{wc} - connate water saturation
t_{BT} - time to break through
W_{iBT} - Water injection at breakthrough
W_{inj} - cumulative water injected, bbl
W_i - the cumulative water injected, bbl.
WOR - water oil ratio
μ_o - Oil viscosity, cp
μ_w - Water viscosity, cp
γ- Specific gravity of the fluids, fraction
α- Angle of inclination, positive up dip, degrees
Ø - porosity

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Appendix

Table A.1 Relative permeability data and water cut of Reservoir OB-63

S_w	0.200	0.300	0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750
K_{ro}	0.900	0.422	0.248	0.184	0.132	0.091	0.057	0.031	0.014	0.000
K_{rw}	0.000	0.040	0.101	0.139	0.188	0.238	0.304	0.385	0.474	0.496
F_w	0.000	0.1594	0.4489	0.7533	0.6017	0.8395	0.9143	0.9613	0.9854	1.0000

Table A.2 Reservoir and Fluid Data for Reservoir OB-63

Discovery pressure	3955 psig
Reservoir temperature	216°f
Stock tank oil initial in place	9.6346 mmSTB
Initial oil formation volume factor, B_o	1.438
API gravity of oil	26°API
Oil viscosity,	1.0 cp
Initial water saturation, S_{wi}	20 %
Connate water saturation, S_{wc}	20 %
Water viscosity,	0.5 cp
Current gas saturation, S_g	10 %
Permeability, k	30 MD
Well depth, d	11 000 ft
Thickness, h	80 ft
Porosity, Ø	0.25
Wellbore radius, r_w	1.0 ft

Table A.3 Waterflood Data for the project

Proposed Flood area, A	45 acres
Proposed Flood pattern	5 spot
Proposed Water Injection Rate	3000 bbl/day