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Water Flooding Process of Oil Recovery in the Niger Delta Region of Nigeria.

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ABSTRACT: Water flooding is a processofhydrocarbon recovery where water is injected through injection wells into the reservoir to recover oil from the production well. It is usually injected in a reservoir rock that has fluid communication with the producing reservoir.Waterflooding is secondary recovery mechanism whose purpose is to maintain and support reservoir pressure thus displacing hydrocarbon towards the producing wellbore. In this study a reservoir in the Niger Delta, Reservoir OZ-70 is used for evaluation and economic analysis of the water flooding project using five spot pattern. Reservoir OZ-70 had oil at the start of the flood to be 2.38MMSTB. The reservoir was left depleted with the unrecovered oil in it. But based on the analysiscarried out on secondary oil recovery by water flooding, 0.98 MMSTB was recovered from 2.38 MMSTB about 41.1% at a breakthrough period of 428 days. When water viscosity was increased from 0.60 to 0.65, 0.99MMSTB about 41.7% was recovered. Economic evaluation of the reservoir oz-70 water flooding project was also performed. Net present value (NPV) was calculated to be $8.74million while internal rate of return (IRR) at a discount rate of 10% was 126.3%. Therefore, since the NPV is greater than zero and IRR greater than hurdle rate (10%) the project is economically viable.

Keywords: secondary oil recovery, water flooding, pressure maintenance hydrocarbon, injection, water, fractional flow, efficiency, displacement, areal sweep, vertical sweep, production.

I. INTRODUCTION

1.1 BACKGROUND INFORMATION

Water flooding is an economic oil recovery technique used in fields without water drive mechanism. Two main classification of water injection projects are as follows.

i. water flooding: This is a process of injecting water water into a reservoir to improve oil recovery by the movement of reservoir oil to the producing well after the reservoir oil has been reduced beyond economic limit.

ii. Water- pressure maintenance :This is done by injecting water into an oil producing reservoir, which boosts the inherent drive energy of the reservoir thus improving crude oil producing capacity of the field before the producible economic limits are attained. (Singh and Rie, 1982)[10].

1.2 Primary Production Mechanisms

The driving forces which cause oil and gas to flow in the well bore can be divided into four basic types; solution gas drive, gas cap drive, water drive and gravity drainage. If more than one of the aforementioned mechanisms are used, the reservoir is called a “combination drive” reservoir, e.g a reservoir with both a free gas cap and external water drive.

a. In water drive reservoir –water flooding can be applied in water drive reservoirs with large size and low production rate, otherwise it is not recommended.

b. Gas cap reservoir -large gas cap reservoirs cannot be candidate for water flooding because they have enough natural reservoir energy to produce. Injecting water may not be recovered in a large gas cap area.However, it can be used in small gas cap area.

c. Gravity drainage - Good gravity drainage reservoircannot be water flooded in order to maximize recovery. However, if gravity drainage is fair water injection can be used to increase production rates.

d. Solution gas drive. Here, the natural energy of the reservoir is lower than that supplied by water injection in terms of efficiency. These reservoirs are good for water flooding. However, at higher gas saturation, larger water volume is required to produce oil at high water cut (singh and kiel, 1982)[10].

II. ANALYSIS OF OIL RECOVERY

2.1.1 Calculation of overall recovery efficiency.

The overall recovery factor (efficiency) RF of a given oil recovery mechanism(secondary and tertiary) is the multiplication of the combined three efficiency factors as described by (Singl and Kiel, 1982)[10].

aAreal sweep efficiency Ea is the ratio of the pattern area that has been displaced by water.

b Vertical sweep efficiency, E_v is the ratio of the cross sectional area of the reservoir that is in contact with the injection water.

c Unit displacement efficiency, E_d is the fraction of initial oil in place displaced by injected water given by Singh and Kiel (1982)[10]

$E_d = S_{oi} - S_{or}/ S_{oi}$ 2.1 where S_{oi} is the initial oil saturation. Volumetric efficiency, E_{vo} is the product of E_a and E_v given by (Singh and Kiel, 1982)

$E_{vo} = E_a \times E_v$ 2.2

The overall recovery efficiency, RF is (Singh and Kiel, 1982)

$RF = E_v \times E_d$ 2.3

Fractional flow equation

$F_w = \frac{1}{1+(\frac{kro}{krw})(\frac{\mu w}{\mu o})}$ 2.4

2.1.2 Mobility Ratio M – It is the ratio of the mobility of the displacing fluid (water) to the mobility of displaced (oil).

$M = \frac{krw \quad \mu o}{kro \quad \mu w}$ 2.5

2.1.3 Areal sweep efficiency at breakthrough. Craig (1971)[3] proposed a graphical connection that correlate the areal sweep efficiency at breakthrough E_{ab+} with the mobility ratio for the five spot pattern. The areal sweep efficiency shown graphically as a powerful function of mobility ratio portrays that a change in the mobility ratio from 0.15 to 10.0 would alter the breakthrough areal sweep efficiency from 100% to 50%. Willhite(1986)[11] presented the following mathematical correlation.

$Eabt = (0.54602036 + 0.03170817/M + 0.30222997/e^M - 0.00509693M)$. where E_{abt} – Areal sweep efficiency at break through and M- Mobility ratio.

2.1.4 Oil recovery calculations

Oil produced, Np before or after break through

Np = Ns Ed EaEv 2.6

When initial gas saturation, Sgi =0, Ed= $(\underline{S_w - S_{wi}}) / (1- S_{wi})$ 2.7

At breakthrough, $E_{dbt} = (\underline{\bar{S}_{wbt} - S_{wi}}) / (1- S_{wi})$ 2.8

$(Np)_{bt} = Ns\ E_{dbt} E_{abt} E_{vbt}$ 2.9

Assuming Ea and Ev are 100%

$(Np)_{bt} = Ns\ E_{dbt}$ 2.10

Before breakthrough $S_{gi} = 0$, water production,Wp = 0 and flow rate of water, q_w=0

After breakthrough, $S_{gi} = 0$, E_a, E_v = 100%

2.2Water flooding process design and operation

2.2.1 Drilling of water injection and production wells. Once water source is certified fit for use in water flooding the water injection well is drilled into the aquifer near the oil reservoir. The wells are drilled to 5 spot patterns.

2.2.2Design of water flood plant. Design of water flood plantincludes(a) water injection rate (b) establishing the water flooding (c) evaluation of production rates and anticipated oil recovery.The most reliable of injection data is obtained from similar water floods located nearby.Mobility ratio is unfavourable if water injectivity exceeds the oil productivity of a producer after fill up while the contrary is true at favourable mobility ratios. For a favourablemobility ratios (m<1), the suggested pattern needs to have more injectors than producers.In this study, five spot pattern with no gas saturation is used to calculate oil recovery at break through by water flooding.

Table2.1: Relative Permeability Data and Water Cut of Reservoir OZ-70

S_w	0.25	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70
K_{rw}	0.00	0.015	0.030	0.068	0.110	0.149	0.213	0.277	0.350
K_{ro}	0.495	0.327	0.260	0.200	0.148	0.102	0.064	0.032	0.000
F_w	0.0000	0.0576	0.1333	0.3120	0.4977	0.6608	0.8161	0.9203	1.0000

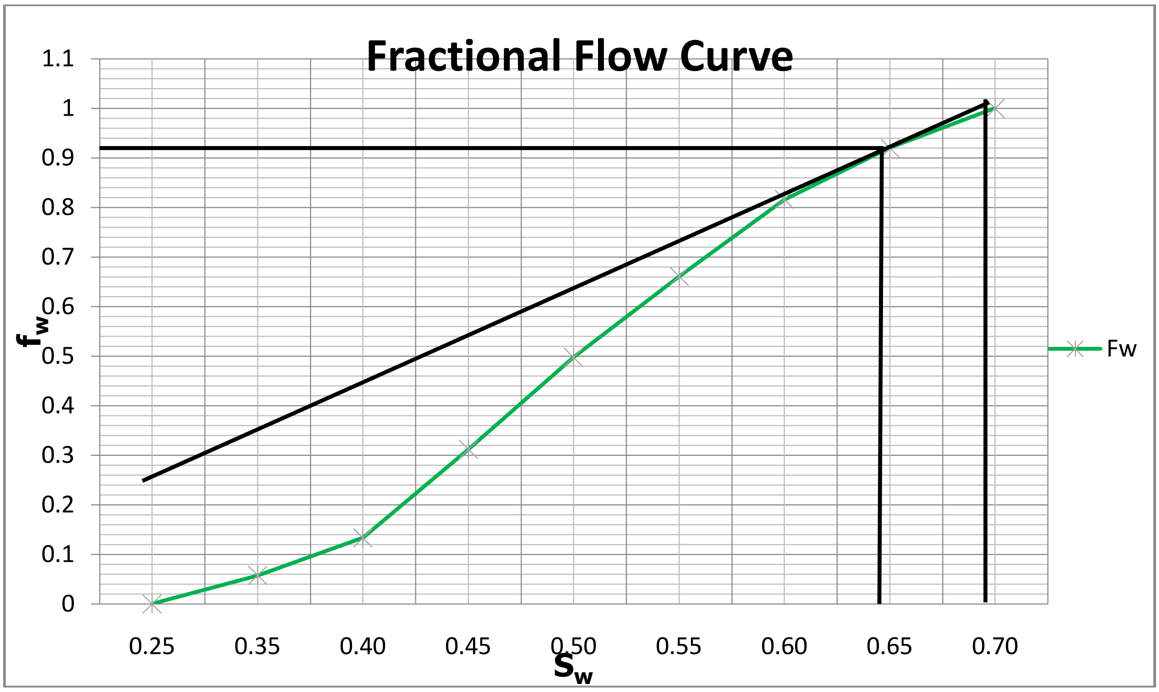

Fig 2.1: Plot of fw against Sw of reservoir OZ-70.

$$f_w \frac{1}{1+\left(\frac{k_{ro}}{k_{rw}} * \frac{\mu_w}{\mu_o}\right)}$$

Table 2.2: Reservoir Properties Data for Reservoir OZ-70

*Flood area (acres)	45
Thickness (ft)	50
Porosity (ϕ)	20
Well bore radius (ft)	1.0
Formation volume factor (B_o)	1.1
*Flood pattern	5spot
Well depth (ft)	10000
Initial water saturation (%)	25
*Water injection rate ($^{bbl}/_{day}$)	2500
Reservoir temperature (^{o}F)	240
Reservoir pressure (psia)	3500
Oil viscosity μ_o (cp)	0.8
Water viscosity μ_w (cp)	0.6
Connate water saturation (%)	2
Average Permeability (md)	35

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Recovery performance is to be predicted with the given data at constant water injection rate.

Phase 1: Initial Calculations

Step 1: Due Volume and Volume of oil at the beginning of flood

PV = 7758 * Flood Area * Formation thickness * Porosity

PV = 7758 * 45 acres * 50 ft * 0.20

PV = 3.49 * 10^6bbl

Volume of oil at the beginning of flood, Ns

Ns = PV (1 – S_{wc})/B_o

Ns = [3.49 * 10^6bbl * (1 – 0.25)]/1.1 = 2.38 * 10^6 or 2.38 MMSTB

Step 2: Plot$f_w$vs$S_w$on a Cartesian scale and ascertain

$S_{wf} = S_{wBT} = 0.640$
$f_{wf} = f_{wBT} = 0.920$
$S_{wBT} = 0.690$
$f_{wBT} = 1.0$

Step 3: Determine K_{ro} at S_{wi} and K_{rw} at S_{wBT} from the relative permeability data;

K_{ro} at S_{wi}, 0.25 = 0.495
K_{rw} at S_{wBT}, 0.693 = 0.338

Step 4: Mobility ratio, M

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

M = (0.338 * 0.6) * (0.8 * 0.495)
M = 0.910

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

According to Willhite (1986)[11]

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

$E_{ABT} = 0.697 \approx 0.7$

Phase 2: Calculation of Recovery Performance at breakthrough

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

$Q_{iBT} = S_{wBT} – S_{wi}$
= 0.690 – 0.250
$Q_{iBT} = 0.440$

Step 2 At breakthrough,cumulative water injection,W_{iBT}

W_{iBT} = (PV) * Q_{iBT} * E_{ABT}
= 3.49 * 10^6bbl * 0.440 * 0.70
W_{iBT}= 1.07 * 10^6 = 1.07 MM bbl

Step 3: Time to breakthrough, tBT

$t_{BT} = \frac{W_{iBT}}{i_w}$ where I_w – water injection rate in $^{bbl}/_{day}$

t_{BT} = 1.07 * 10^6bbl / 2500 $^{bbl}/_{day}$

t_{BT} = 428 days

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

$$E_{DBT} = \frac{(S_{wBT} - S_{wi})}{(1 - S_{wi})}$$

= [0.690 – 0.25] / (1 – 0.25)

E_{DBT} = 0.440/ 0.75 = 0.5867

Step 5: At breakthrough,cumulative oil production

$[N_p]_{BT} = N_s E_{DBT} E_{ABT}$
= 2.38 MMSTB * 0.5867 * 0.70
$[N_p]_{BT}$ = 977442.2 STB

2.3 Economic analysis of secondary oil recovery by water flooding for reservoir OZ-70 in the Niger Delta

2.3.1 Investment costs

The costs mean whatever it takes for the installation of the project facilities and the operation of the facilities. It includes investment costs and the operating cost.

- For 5-spot pattern, the cost of drilling and completing water injection wells are stated below:
- The cost of drilling and completing a well is $150 per foot
- For a total depth of 10 000 ft, the cost of drilling and completing the well is

$150 * 10000 ft = $1.5 million

- Cost of installation of well head structures is $10000

Total cost of one well is $1.5 million + $10000 = $1.51 million

Total cost of the 5 wells is $1.51 million * 5 = $7.55 million, (Philips, 2009)[9]

ii) water injection pump installation cost, take 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)[9]

- installing a gathering system for the water collection will cost an assumed value of $60,000.
- The estimated cost of connecting water pipelines to deliver the water about 10 miles away from the oil well where the water well is, execution of associated civil works and maintenance of water facility for less than two years is $866 600, (Oil Serve Nigeria, Jan, 2004)[8]

The total cost of water and water lines is $2000 + $60,000 + $866 600 = $928,600.

Total investment cost is 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 $7.55 million + $208,000 + $928,600 = $8.69 million.

2.3.2 Operating Costs

Operating cost = Management costs+Labourcosts + maintenance costs Labour costs: Total number of employees is assumed to be 40 and a salary average of $5 000 per month per employee. For the 40 employees,the Total labour costs for each month would equate to 40 * $5 000 = $200 000.

Annually labour costs = $200 000 * 12 = $2.4 million

Maintenance costs: These are majorly spare parts usedto the tune of $1.95 million per year; fixed assets repair to the tune of $795,000/year; operating outsourced services to the tune of $4.05 million/year.

Total maintenance costs per year = $1.95 million + $795,000 + $4.05 million = $6.80 million.

Management costs = $810,000

Annual Operating cost = $2.4 million + $6.08 million + $810,000= $10.01 million.

III. RESULTS AND DISCUSSION

3.1 Results: Recovery analysis for Reservoir OZ-70

Table 3.1: Oil recovery data for the water flooding project of reservoir OZ-70

Water viscosity	0.6
Proposed flood pattern	5 Spot
Proposed water injection rate	2500
Pore volume at start of flood	3.49 *10^6bbl
Vol. of oil at start of flood, Ns	2.38 MMSTB
Mobility ratio, M	0.910
Areal Sweep Efficiency at breakthrough, E_{ABT}	0.7
Cumulative water injection at breakthrough, W_{iBT}	1.07 MM bbl
Time to breakthrough, t_{BT}	428 days
Displacement efficiency at breakthrough, E_{DBT}	0.5867
Cumulative oil production at breakthrough, $[N_P]_{BT}$	977442.2 STB

Profitability Analysis:

The price of crude is assumed to be $40 per barrel. Therefore,

For 977442.2 STB = 40 * 977442.2 = $39.1 M

Table 3.2: Effect of change in water viscosity for reservoir OZ-70

Parameters	Water viscosity value at 0.6	Water viscosity value at 0.65
Areal Sweep Efficiency at breakthrough, E_{ABT}	0.70	0.71
Mobility Ratio, M	0.910	0.840
Cumulative oil production at breakthrough, $[N_P]_{BT}$	977442.2 STB	991405.7 STB
$[N_P]_{BT}$ as % Ns	41.1%	41.7%

Net Present Value of Reservoir OZ-70

Net Present Value (NPV) is anindicator of economic viability of a project

Table 3.3: Cash flow for the project reservoir OZ-70

Time (yr)	INVESTMENT ($M)	REVENUE ($M)	OPEX ($M)	NCF ($M)	CUM NCF ($M)	PV @ 10% ($M)
0	8.69	0	0	(8.69)	(8.69)	(8.69)
1	0	30.1	10.01	20.09	11.40	18.26
2	0	9.0	10.01	(1.01)	10.39	(0.83)
					TOTAL	17.43

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NPV = 8.74

Table 3.4: of Oil Price and NPV for Reservoir OZ-70

OIL PRICE ($/bbl)	NPV @ 10% ($/bbl)
20	(8.71)
30	0.02
40	8.74
50	17.47
60	26.09

From Table 4.4 and Fig 4.1, the project will not be economically viable at crude oil price below $30 but can be carried out at $30 and above.

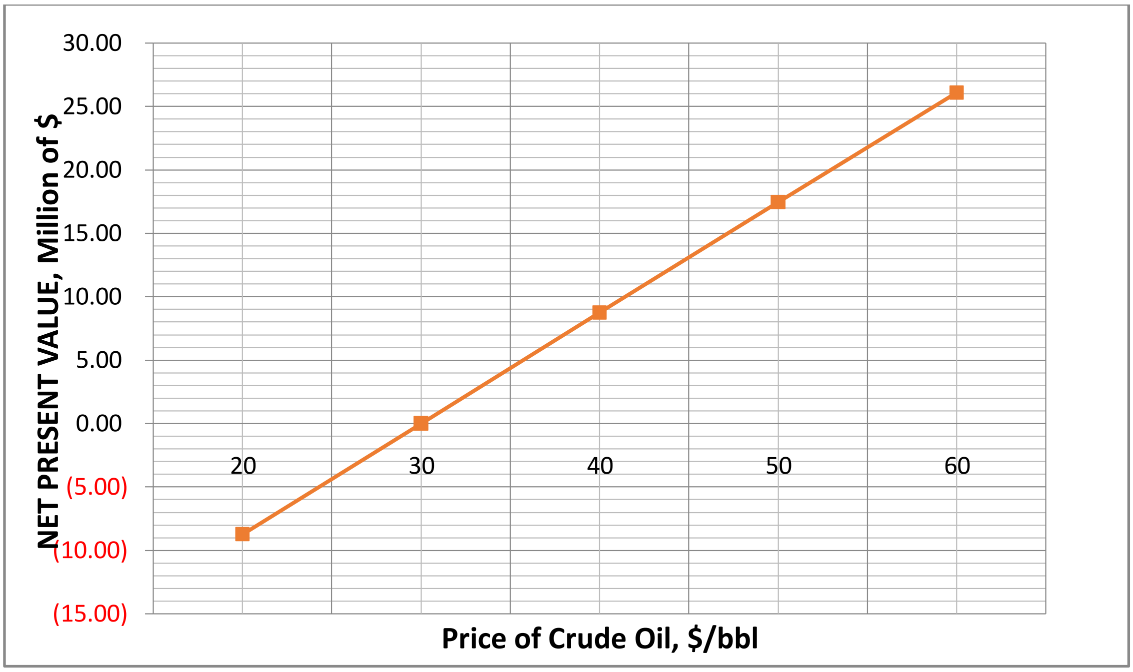

Fig 3.1: Plot of NPV against Crude Oil Price for Reservoir OZ-70 Project

Table 3.5: Relative Permeability Data for Reservoir OZ-70

S_w	0.25	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70
K_{rw}	0.00	0.015	0.030	0.068	0.110	0.149	0.213	0.277	0.350
K_{ro}	0.495	0.327	0.260	0.200	0.148	0.102	0.064	0.032	0.000

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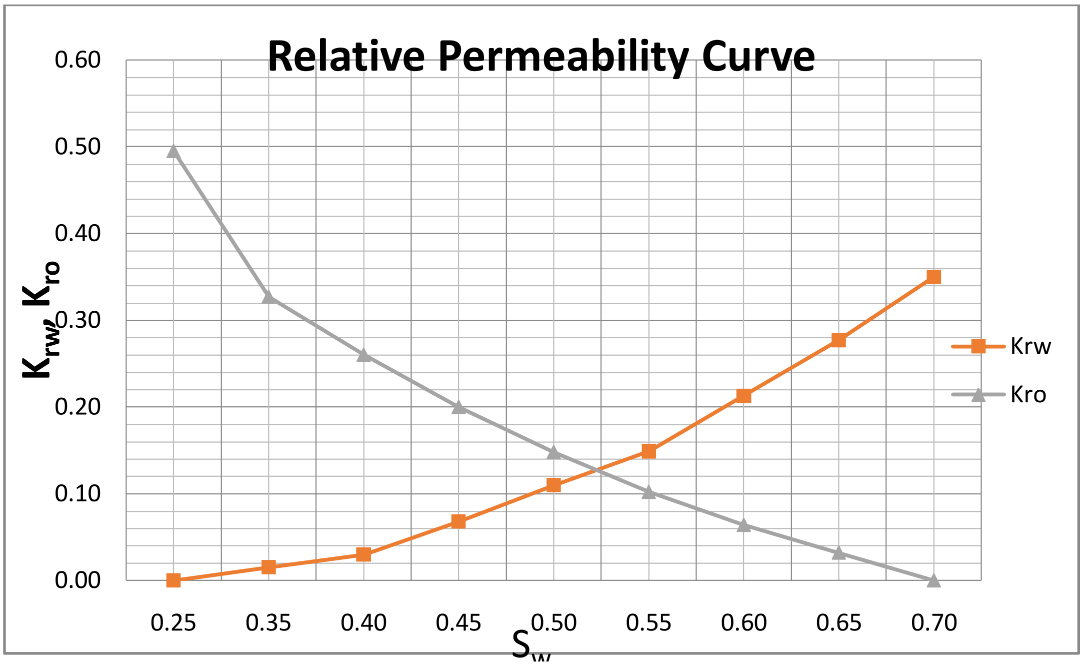

Fig 3.2: Plot of relative permeability against water saturation for Reservoir OZ-70 project

Table 3.6: CAPEX and NPV for Reservoir OZ-70 Project

CAPEX ($M)	**NPV ($M)**
4.30	13.13
6.40	11.03
8.69	8.74
10.20	7.23
12.95	4.48
15.65	1.78
18.46	(1.03)

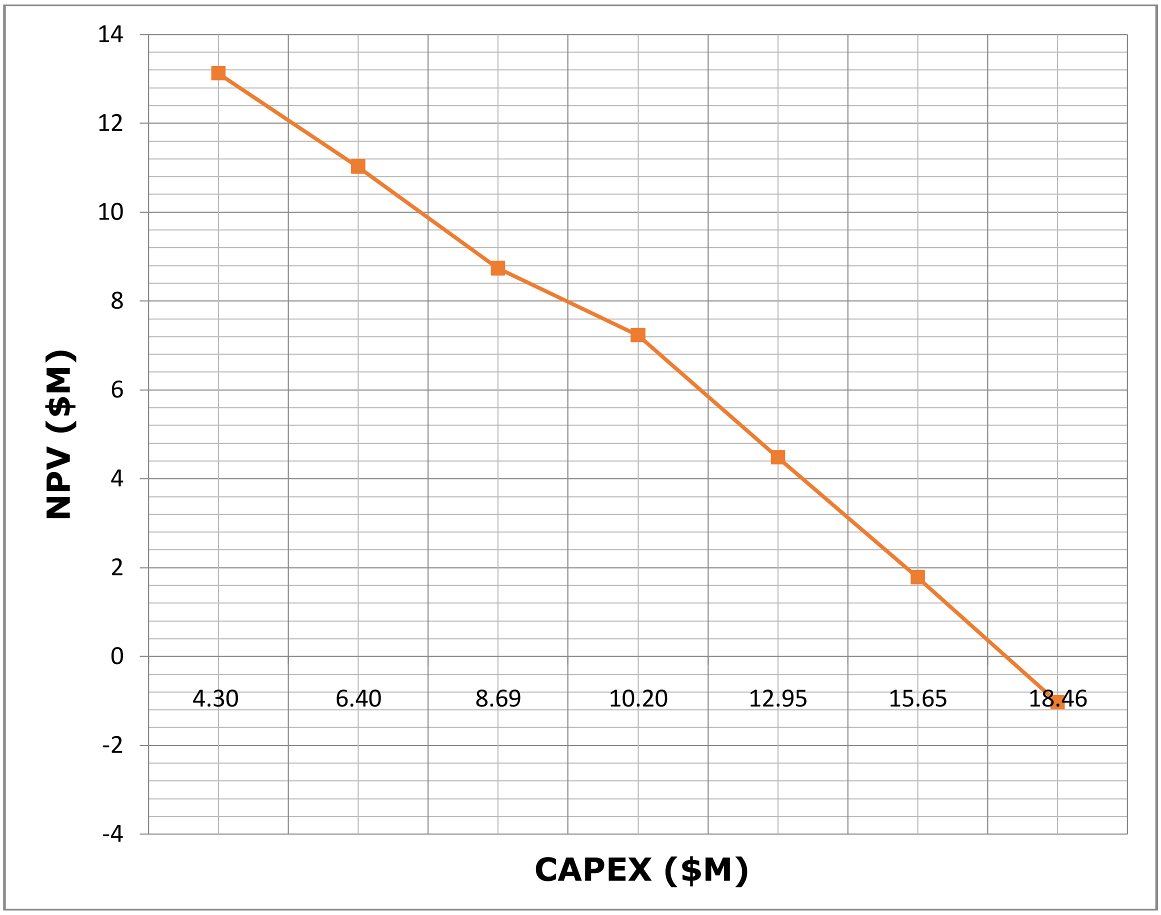

Fig 3.3: Plot of NPV against CAPEX for Reservoir OZ-70 project

From Table 4.6 and Fig 4.3, at capital expenditure greater than $M 16.0, the project will no longer be feasible since the NPV value will be negative.

Table 3.7Discount rate and NPV for the Reservoir OZ-70 Project

DISCOUNT RATE (%)	NPV ($M)
10	8.74
30	6.16
50	4.26
70	2.78
90	1.60
110	0.65
130	(0.15)
150	(0.82)

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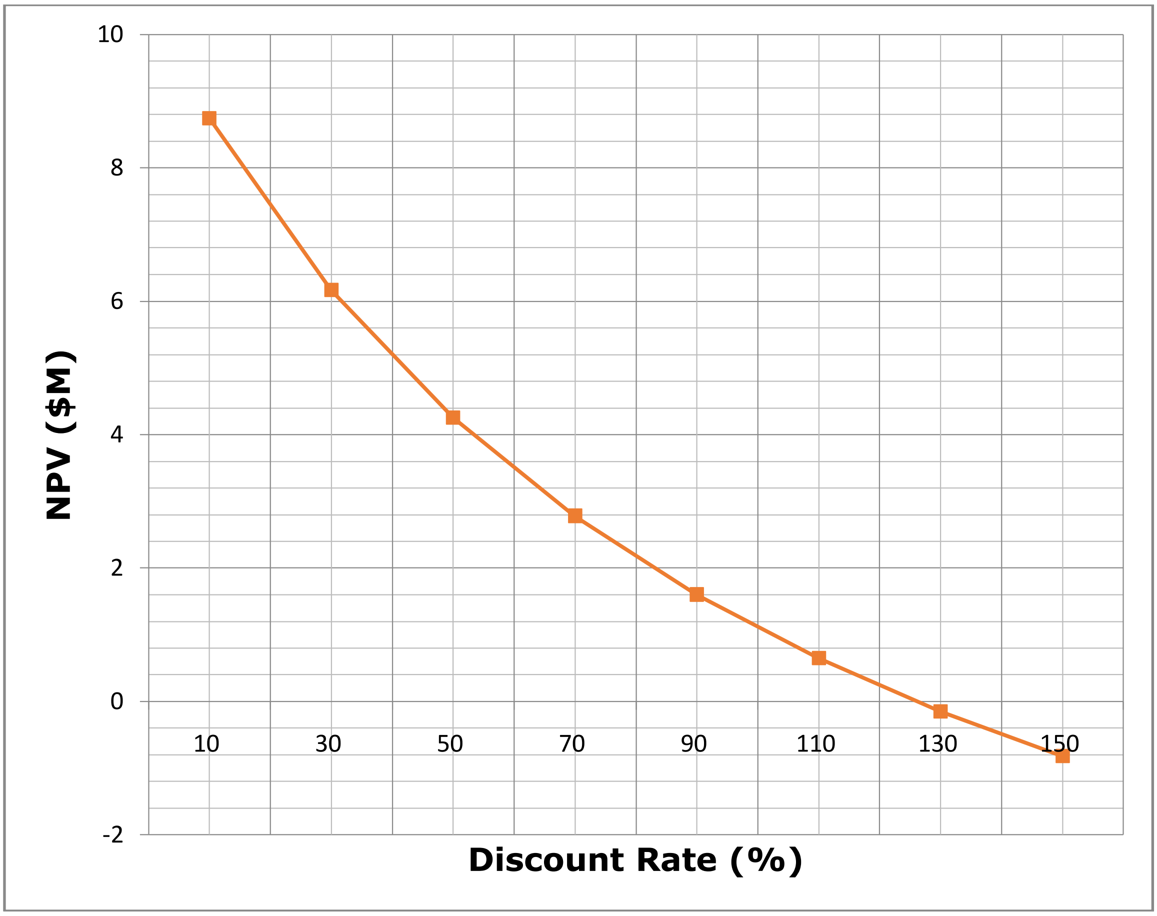

Fig 3.4: Plot of NPV against Discount Rate for Reservoir OZ-70 project

3.2 Discussion.

From the table 4.1 and 4.2 above the cumulative oil production at breakthrough which is about 428 days is 0.97MMSTB covering about 41.1% 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 0.7 and 0.5867 respectively.

Increasing water viscosity from 0.60 to 0.65 reduces the mobility ratio from 0.910 to 0.840, the areal sweep efficiency will change from 0.70 to 0.71 and the cumulative oil production at breakthrough would be 0.99MMSTB instead of 0.97MMSTB.

NPV for the water flooding project

From table 4.6 and fig 4.3, the capex at which NPV is zero is the Capex limit for viability of the project. Anything more than that amount, the project would not be profitable any more

From table 4.4 and Fig 4.1, the crude oil price at which the NPV is zero which is the price limit of crude oil at which the project is profitable is $30/bbl. This means that when the crude oil price goes below $30/bbl the project would not be profitable any more.

Internal rate of return IRR

The rate of return at which the net present value (NPV) of all possible cash flows in a given investment equate to zero is the Internal Rate of return. Investing in a project with a higher internal rate of return (IRR) is highly recommended. From Table 4.6 and Fig 4.4 internal rate of return is calculated to be 126.3%.

IV. CONCLUSION

Waterflooding operation carried out in a reservoir oz70 located in the Niger Delta region of Nigeria was successful and profitable as shown by the results obtained.

Nomenclature.

bbl = barrel,bbl/day = barrel per day, Bbl/acre ft = barrel per acre ft,Bbl/ft = barrel per foot, , Bor = formation volume factor of oil after water flooding,CUMNCR – Cumulative net cash recovery, E_A = areal sweep efficiency,ED =

displacement efficiency, E_V = vertical sweep efficiency,Exp = expenseFt = foot/feet,FVF = formation volume factor, Fw = fractional water flow,in = inch,I = initial investment, K_o = effective permeability to oil, md,E_{ABT} = areal sweep efficiency at breakthrough, Boi = formation volume factor of oil at start of flood, bbl/STBK_w = effective permeability to water, md, K_{rw}= relative permeability to water at $S_{or,}K_{ro}$= relative permeability to oil at S_{wi},M = mobility ratio,MM = million,,MMSTB = million stock tank barrel,N = No. of days the project will last,NPV = Net present value,Np = cumulative oil produce, STB,Ns = initial oil in place at the start of flood, STB, NCF = net cash flow,NPV = net present value,OPEX = operating expenses,DV = pore volume,Rev = revenue,S_{wi} = initial water saturation at the beginning of the flood, RF = overall recovery factor,ROS = residual oil saturation,S_{gi} = initial gas saturation,S_{or} = residual oil saturation,S_{oi} = initial oil saturation at the beginning of flood,.$\bar{S}_o$ = average oil saturation in the flood pattern at a particular point during the flood,$\bar{S}_w$ = average water saturation in the swept zone,W_{inj} = cumulative water injected, bbl$_o$Sgi = initial gas saturation at the beginning of the flood,S_g = gas saturation,t_{Bi} = time to break through,W_{IBT} = water injection at break through,MD = millidarcy,μ_o = oil viscosity, cp , μ_w = water viscosity, cp , ϕ = Porosity

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