

# WATER FLOOD ANALYSIS TO PREDICT ADDITIONAL OF OIL RECOVERY FROM OIL RESERVOIR

by  
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## ABSTRACT

*Water injection, the most widespread secondary method of oil recovery, is a pattern flooding when water is injected over the entire oil bearing area of the reservoir.*

*The main reason why this method is so widely used is the high recovery achieved when water is the displacing agent both in the case of a natural water drive and when water is injected into reservoir artificially. However, if the flooding operation is carried out carelessly, the result may be entirely negative or wasteful operation.*

*One of the primary objectives of water flood analysis is to predict additional oil recovery obtained by water flooding from oil reservoirs.*

*This paper presents a practical use of water flood method for formation evaluation of reservoir hydrocarbon and provides information that will be of practical value to geologists and engineers involved in the interpretation of water flood data; these then become the reference for an economic projection of the profitability of the water-flood.*

## I. INTRODUCTION

Waterflood is the application of artificial techniques to increase the proportion of oil that can be extracted from a crude oil reservoir, beyond the amount that flows naturally or is pumped to the surface through producing wells. Oil production from reservoirs by natural (primary) drive mechanisms is often an inefficient process which may leave considerably more "residual" oil trapped behind the reservoirs than can be produced.

The objective of water flood analysis is to predict the performance of reservoir under water flooding as a secondary recovery method. In a water-drive displacement mechanism, three principle factors control the proportion of reservoir hydrocarbons remaining at depletion.

### A. Contact Factor

The contact factor of a reservoir is an expression of the amount of the reservoir that bypassed by the displacing water, for various physical reasons. If the reservoir contains sizeable zones of shale or silt,

faults, extreme permeability variations or tight zones, the contact factor will be poor.

### B. Sweep Efficiency

The mobility of fluids in a reservoir controls the sweep efficiency (mobility is the permeability of a rock to a fluid, divided by the fluid's viscosity).

Sweep efficiency is usually determined as a function of the ratio of water mobility to oil mobility, and can be improved in an oil reservoir either by raising the water viscosity by using chemicals or by lowering the oil viscosity by thermal techniques.

### C. Displacement Efficiency

This is the pore system of the reservoir that principally governs displacement efficiency; the productions controlled by the degree of pore interconnection, the size of the pore throats, the fluid and rock interfacial tensions, and the resulting pressure required to move the various phases (gas, oil, and water) through the system.

Direct dynamic displacement has generally been a standard laboratory technique for waterflooding of

core samples. In particular this method expresses the characteristics of water injection into a permeable medium where oil is the displaced phase.

**II. ANALYSIS METHODS**

The oil displacement efficiency of a water flood in the field can be predicted from the water-oil relative permeability characteristics and the water and oil viscosities.

The established procedure is to construct a plot of fractional flow of water versus water saturation. Ignoring capillary pressure effects, fractional flow equation is as follows :

$$f_w = \frac{1 - \frac{k}{Ut} \frac{k_{ro}}{\mu_o} (g \cdot dp \cdot \sin \alpha d)}{1 + \frac{u_w}{\mu_o} \frac{k_{ro}}{k_{rw}}} \dots \dots \dots (1)$$

Where :

- $f_w$  = fraction of water in the flowing stream passing any point in the rock (i.e watercut)
- $k$  = formation permeability
- $k_{ro}$  = relative permeability to oil
- $k_{rw}$  = relative permeability to water
- $Ut$  = total fluid velocity
- $\mu_o$  = oil viscosity
- $\mu_w$  = water viscosity
- $g$  = acceleration due to gravity
- $dp$  = water-oil density difference
- $\alpha d$  = angle of formation dip to the horizontal.

In so called practical units, the equation becomes :

$$f_w = \frac{1 - 0.00488 \frac{k \cdot k_{ro}}{\mu_o} \frac{A}{qt} (dp \cdot \sin \alpha d)}{1 + \frac{u_w}{\mu_o} \frac{k_{ro}}{k_{rw}}} \dots \dots (2)$$

Where permeability is in *mD* ; viscosity in *cp* ; area (*A*) in *sq.ft* ; *qt* ( flow rate ) in *BPD* ; and density difference in *gm/cc*.

In this paper three methods of water flood analysis will be discussed, namely Buckley-Leverett, Dykstra-Parson and Stiles methods.

**A. Buckley-Leverett Method**

This method is based on the equation Fractional Flow Formula in horizontal reservoir and simplified as follows :

$$f_w = \frac{1}{1 + \frac{u_w}{\mu_o} \frac{k_{ro}}{k_{rw}}} \dots \dots \dots (3)$$

Calculation procedures of prediction are as follows :

- a. Define oil-water relative permeability data, fluid properties and the relation between  $f_w$  versus  $S_w$ , then plot  $f_w$  against  $S_w$  on cartesian coordinate paper.
- b. Draw the tangent line to fractional flow curve, this gives the  $S_w$  value of the flood front at breakthrough point.
- c. Calculate analytically the rate change in the fractional flow ( $f_w'$ ), as a function of the change in the flood front  $S_w$ .

$$f_w' = df_w/dS_w = f_w/S_w \dots \dots \dots (4)$$

The range  $S_w$  value are as follows :

$$S_{wsz} \leq S_w \leq (1 - S_{or}) \dots \dots \dots (5)$$

- d. Calculate water-oil production ratio (*WOR*), for each of  $S_w$  point as follows :

$$WOR = B_o / (1/f_w) - 1 \dots \dots \dots (6)$$

Then calculate the *PV* of cumulative injected water (*Qi*)

$$Q_i = 1 / (df_w/dS_w)_{S_w} \dots \dots \dots (7)$$

- e. Average water saturation ( $S_w$ ), can be determined using *Welge* equation.

$$S_w = S_w + (Q_i \times f_o) \dots \dots \dots (8)$$

where  $f_o = (1 - S_w)$

- f. Calculate the Recovery Factor using equation :

$$R.F = \frac{(S_w - S_{wi})}{(1 - S_{wi})} \times (B_{oi}/B_o) \dots \dots \dots (9)$$

where :  $S_{wi} = S_{wc}$



- g. Then plot *WOR* versus *R.F* on cartesian coordinate paper.
- h. Organize steps (c) through (g), hence for the particular value *WOR* of 49 or water cut of 98 %, then define recovery factor.

**B. Dykstra-Parson Method**

Dykstra-Parson method is applied as the second approach in water flood analysis. In this method, the water flood recovery is considered to be influenced by mobility ratio and permeability variation. The mobility ratio (*M*) is estimated using the equation :

$$M = (Kr_w/\mu_w) \times (\mu_o/Kr_o) \dots\dots\dots (10)$$

where :

- Kr<sub>o</sub>* = oil relative permeability at *Swc*
- Kr<sub>w</sub>* = water relative permeability *S<sub>or</sub>*
- $\mu_o$  = oil viscosity at current pressure
- $\mu_w$  = water viscosity

The permeability distribution was defined from core sample data.

The permeability variation (*V*) is estimated with the following equation :

$$V = (\bar{K} - K_j)/\bar{K} \dots\dots\dots (11)$$

where :

- $\bar{K}$  = average permeability
- $K_j$  = permeability of 84 % probability

Using a mobility ratio and a permeability variation, the fractional oil recovery at producing water oil ratio of 1, 5, 25 and 100 can be estimated. The graphical technique for this method generated by Johnson are shown in Figure 6 through 9.

The calculated water flood recovery is the plotted vs *WOR*.

By applying a *WOR* of 49 or a water cut of 98 % corresponding to a cumulative oil production, the calculation is performed as follows :

- a. Arrange all permeability data in descending order, then develop cumulative frequency distribution.  
Plot the cumulative probability values versus log of permeability on probability paper and draw the

straight line through the data points. Then, calculate permeability variation (*V*) using values from the straight line.

$$V = \frac{K_{50} - K_{84.1}}{K_{50}} \dots\dots\dots (12)$$

where :

- K<sub>50</sub>* = The median permeability with 50 % of the permeability values being greater than or equal to it, md.
- K<sub>84.1</sub>* = The permeability with 84.1 % of the permeability values being greater than or equal to it, md.

- b. Calculate the mobility ratio (*M*) using equation :

$$M = (Kr_w/\mu_w) \times (\mu_o/Kr_o)$$

where relative permeability to oil and water are obtained for a specified *Sw* from water-oil relative permeability vs *Sw*.

- c. Correlation of permeability variance (*V*) data versus mobility ratio (*M*), generated by Johnson for different *WOR* value of 1, 5, 25, and 100 as shown in Figure 6 through Figure 9 are used to estimate the recovery factor (*R*). Hence for a particular value of *V* and *M*, recovery factor then can be obtained.
- d. Then plot recovery factor (*RF*), versus water oil ratio (*WOR*), on cartesian coordinate paper.
- e. Hence, using the above curve for a particular *WOR* value or water cut, the recovery factor can be determined.

**C. Stiles Method**

In Stiles method, an oil reservoir is visualized as a layered reservoir, with each layer having a different permeability. With the exception of the permeability of the rock and the fluid properties are considered to be the same for all layers. It also considers the influence of permeability distribution.

In Stiles method, the expected maximum water flood recovery is expressed as :

$$R = \frac{(S_{oi} - S_{or})}{S_{oi}} \times \frac{B_{oi}}{B_o} \dots\dots\dots (13)$$

where :

- $R$  = maximum water flood recovery
- $Soi$  = initial oil saturation
- $Sor$  = residual oil saturation
- $Boi$  = initial oil volume factor
- $Bo$  = current oil volume factor

Calculation procedures are as follows :

- a. Develop capacity distribution of permeability, then plot the cumulative capacity versus cumulative thickness, then generate the parameter of dimensionless permeability.
- b. Plot the dimensionless permeability versus cumulative thickness.
- c. Using the dimensionless permeability and cumulative capacity generate the Recovery Factor.
- d. Water cut is developed from cumulative capacity and mobility ratio.

$$\text{Define } A = Krw/Kro \times \mu o/\mu w \times Bo \dots\dots (14)$$

Where :  $Kro$  at  $Swc$  and  $Krw$  at  $Sor$

Use the "A" parameter to determine the water cut.

- e. Plot Water Cut against Recovery Factor. Maximum water flood oil recovery is defined using the equation as,

$$\text{Recovery Maximum} = (Soi - Sor)/Soi \times (Boi/Bo) \dots\dots (15)$$

### III. CASE STUDY OF WATER FLOOD ANALYSIS

Water flood analysis in this study was performed on the clastic carbonate reservoir, having original oil in place of 70.3 MMSTB. Primary oil recovery estimation performed by decline curve analysis was 24.2 % of OOIP, corresponding to an ultimate oil recovery of about 17.01 MMSTB. The equifer size was calculated to be 49 times the oil volumes.

#### A. Application of Buckley-Leverett Method

Calculation steps of prediction are as follows :

- a. Using oil-water relative permeability data, fluid properties and the relation between tabulated  $f_w$

versus  $Sw$  as presented in Table 1 and  $KwKo$  relative permeability data in Figure 1, then plot  $f_w$  vs  $Sw$  on cartesian coordinate paper, presented in Figure 2.

- b. Draw the tangent line to fractional flow curve as indicated in Figure 3, this gives the water saturation value of the flood front at breakthrough.
- c. Calculate analytically the rate change in the fractional flow,  $f_w'$ , as a function of the change in the flood front water saturation.

$$f_w' = df_w/dSw = f_w/Sw$$

The range value are as follows :

$$Swsz \leq Sw \leq (1 - Sor)$$

where  $Swsz = 0.411$

- d. Calculate water-oil production ratio ( $WOR$ ) for each of  $Sw$  point as follows :

$$WOR = Bo / (1/f_w) - 1$$

- e. Then calculate the  $PV$  of cumulative injected water ( $Qi$ )

$$Qi = 1 / (df_w/dSw)_{sw}$$

- f. Average water saturation  $Sw$ , can be determined using Welge equation.

$$\bar{Sw} = Sw + (Qi \times fo)$$

Where  $fo = (1 - Sw)$

- g. Calculate the Recovery Factor using equation :

$$R.F = \frac{(Sw - Swi)}{(1 - Swi)} \times (Boi/Bo)$$

where :  $Swi = Swc$

- h. Then plot  $WOR$  against  $R.F$  on cartesian coordinate paper as shown in Figure 4.
- i. Organize steps (c) through (g) as presented in Table 2, hence for the particular value  $WOR$  of 49 or water cut of 98 % recovery factor then equal to 43.25 %

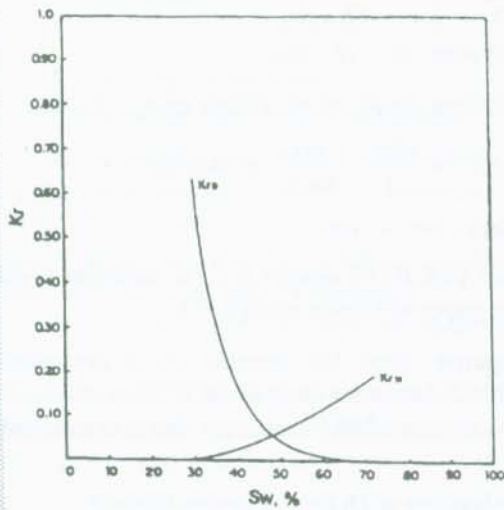
#### B. Application of Dykstra-Parson Method

In the Dykstra-Parson method, recovery is calculated by taking into consideration the permeability variation of the layer and the mobility ratio.

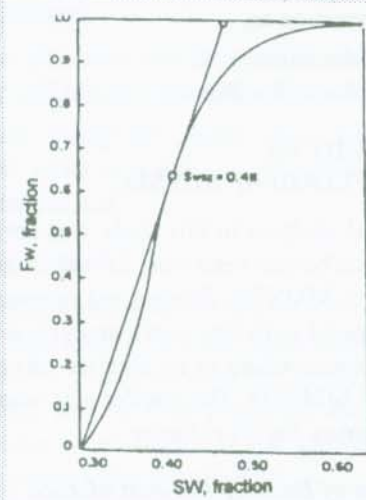


**Table 1**  
Water-oil relative permeability data with fw and Sw relationship

Sw	Kro	Krw	Kro/Krw	$\mu_w/\mu_o$	fw
0.300	0.6350	0.000	--	0.123	0.0000
0.342	0.3620	0.0078	46.4103	0.123	0.1491
0.384	0.2032	0.0194	10.4742	0.123	0.4370
0.426	0.1162	0.0341	3.4076	0.123	0.7047
0.468	0.0641	0.0519	1.2351	0.123	0.8681
0.510	0.0362	0.0725	0.4993	0.123	0.9421
0.552	0.0197	0.0954	0.2065	0.123	0.9752
0.594	0.0108	0.1190	0.0908	0.123	0.9890
0.636	0.0043	0.1437	0.0299	0.123	0.9963
0.678	0.0005	0.1705	0.0029	0.123	0.9996
0.720	0.0000	0.1960	0.0000	0.123	1.0000



**Figure 1**  
Water-oil relative permeability curve



**Figure 2**  
Fw and Sw relationship

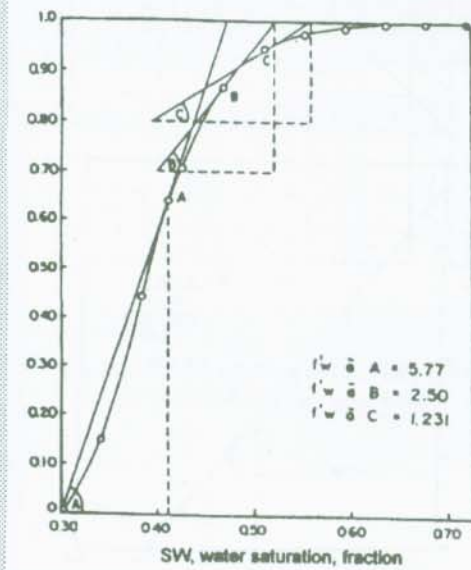


**Table 2**  
Water flood displacement performance

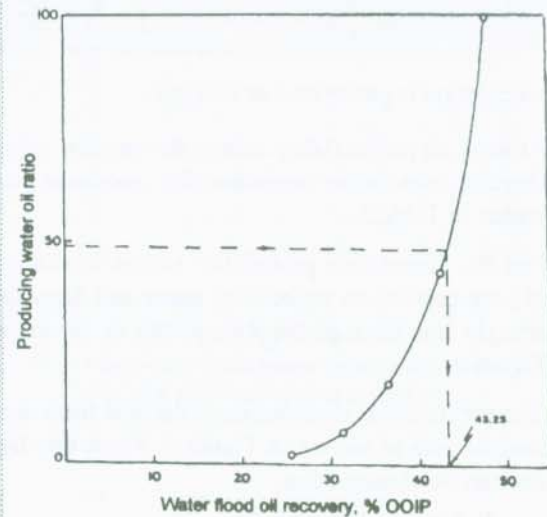
Sw	fw	dfw/dsw	QI	Sw	Sw-Swi	WOR	R.F
0.411	0.6400	5.7700	0.170	0.472	0.172	1.98	24.38
0.468	0.8681	2.5000	0.400	0.521	0.221	7.33	31.32
0.510	0.9421	1.2310	0.812	0.557	0.257	18.13	36.42
0.552	0.9752	0.5250	1.915	0.599	0.229	43.81	42.37
0.594	0.9890	0.2558	3.909	0.637	0.337	100.6	47.76
0.636	0.9963	0.1056	9.470	0.671	0.371	299.9	52.58
0.678	0.9996	0.0400	25.000	0.688	0.338	2784	54.99
0.720	1.0000	0.0114	87.720	0.720	0.420	--	59.52

Notes: WOR =  $Bo / (1/f_w) - 1$   
 Boi = 1.1051  
 Bo = 1.1140

R.F. =  $(Sw - Sw_i) / (1 - Sw_i) \times (Boi / Bo)$   
 Sw = Swc = 0.30



**Figure - 3**  
Sw value of flood front at breakthrough determination



**Figure - 4**  
WOR and oil recovery relationship



Table 3  
Frequency distribution of permeability calculation

Permeability Range (MD)	Average Perm. (K)	Frequency	Freq. Fract. (F)	Cum. Freq. (fract)	I-Cum. Freq. (fract)
0.31 - 0.63	0.52	14	0.0660	0.0660	0.9340
0.63 - 1.25	0.91	46	0.2170	0.2838	0.7170
1.25 - 2.50	1.73	43	0.2028	0.4858	0.5142
2.50 - 5.00	3.43	31	0.1462	0.6321	0.3673
5.00 - 10.0	8.55	30	0.1415	0.7736	0.2264
10.0 - 20.0	13.17	24	0.1132	0.8868	0.1132
20.0 - 40.0	26.22	15	0.0707	0.9575	0.0425
40.0 - 80.0	52.97	3	0.0142	0.9717	0.0283
80.0 - 160	101.91	4	0.0819	0.9908	0.0094
160 - 320	210.00	1	0.0047	0.9953	0.0047
320 - 640	480.00	0	0.0000	0.0000	0.0047
640 - 1280	699.80	1	0.0047	1.0000	0.0000
		$\Sigma = 212$			

The calculation is performed as follows :

- Arrange all permeability data in descending order. Develop cumulative frequency distribution as presented in Table 3.

Plot the cumulative probability values versus log of permeability on probability paper and draw the straight line through the data points as shown in Figure 5.

The permeability distribution is defined from core sample data as shown in Figure 5. From this figure can be obtained that,

$$K\text{-Average } (\bar{K}) = 2.63$$

$$K_j = 0.61$$

Calculate permeability variation ( $V$ ), using values from the straight line.

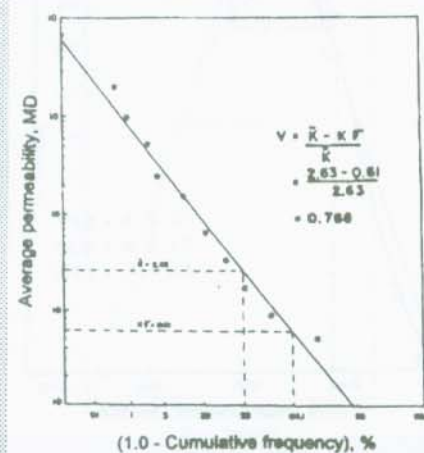


Figure 5  
Average permeability vs cumulative frequency



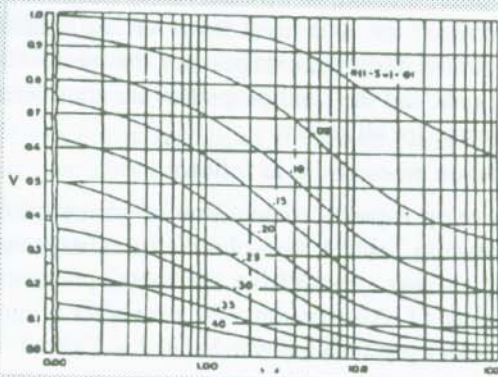


Figure 6  
Permeability variation vs mobility ratio  
for WOR of 1 (After Johnson)

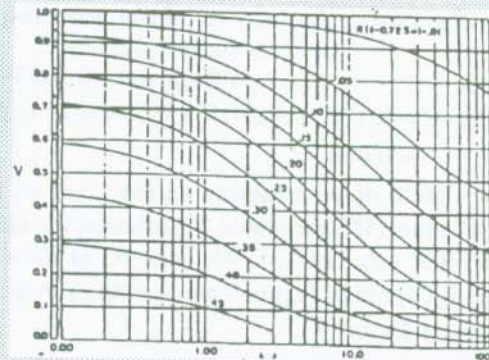


Figure 7  
Permeability variation vs mobility ratio  
for WOR of 1 (After Johnson)

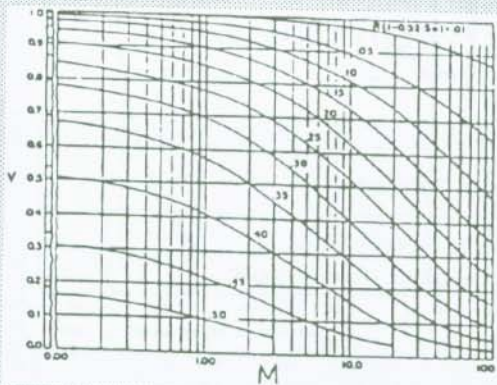


Figure 8  
Permeability variation vs mobility ratio  
for WOR of 1 (After Johnson)

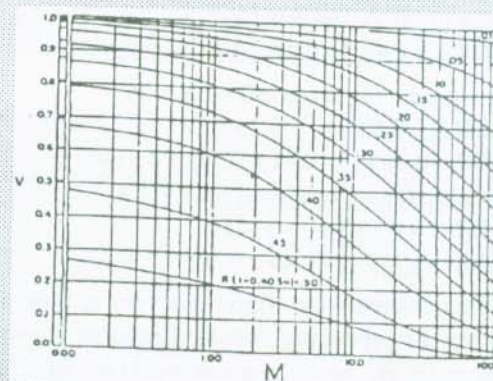


Figure 9  
Permeability variation vs mobility ratio  
for WOR of 1 (After Johnson)

$$V = \frac{K_{50} - K_{84.1}}{K_{50}}$$

$$V = \frac{2.63 - 0.61}{2.63} = 0.768$$

- b. Calculate the mobility ratio ( $M$ ) using equation (10):

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

where relative permeability to oil and water are obtained for a specified  $S_w$  from Figure 1.

at  $S_w = 0.472$  ---->  $K_{rw} = 0.0539$

at  $S_w = 0.30$  ---->  $K_{ro} = 0.635$



$S_w = 0.472$  The average water saturation at breakthrough point.

$S_w = 0.30$  Connate Water Saturation

$\mu_o$  and  $\mu_w$  Viscosity of oil and water respectively at current pressure  
 $\mu_o = 2.4486$  cp,  $\mu_w = 0.3013$  cp

Then  $M = (0.0539)/(0.3013) \times (2.4486)/(0.635) = 0.690$

- c. Correlation of permeability variance ( $V$ ) vs mobility ratio ( $M$ ), generated by Johnson for different  $WOR$  value of 1, 5, 25, and 100 as shown in Figure 6 through Figure 9 are used to estimate the recovery factor ( $R$ ).

Fractional oil recovery ( $ER$ ) can be calculated based on water oil ratio data, as follows :

For a producing water-oil ratio = 1.

$ER (1 - S_w) = 0.0875$   
 $ER = 0.0875/(1 - 0.30) = 0.1250$

For a producing water-oil ratio = 5.

$ER (1 - 0.72 S_w) = 0.170$   
 $ER = 0.170/(1 - 0.72 \times 0.30) = 0.2168$

For a producing water-oil ratio = 25.

$ER (1 - 0.52 S_w) = 0.265$   
 $ER = 0.265/(1 - 0.52 \times 0.30) = 0.3140$

For a producing water-oil ratio = 100.

$ER (1 - 0.40 S_w) = 0.325$   
 $ER = 0.325/(1 - 0.40 \times 0.30) = 0.3693$

The calculated water flood recovery is then plotted versus producing water-oil ratio as shown in Figure 10. By applying a water-oil ratio of 49 or a water cut of 98 % the water flood recovery will be 34.9 % corresponding to a cumulative oil production of 24.53 MSTB.

Hence for a particular value of  $V = 0.768$  and  $M = 0.690$ , recovery factor then can be obtained as shown below.

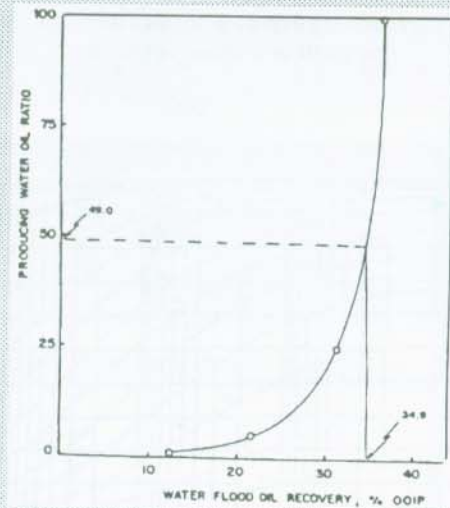
- d. Then plot recovery factor ( $RF$ ), versus water oil ratio ( $WOR$ ), on cartesian coordinate paper as shown in Figure-10.
- e. Hence, using the above curve for a particular  $WOR$  value of 49 or water cut 98 %, the recovery factor of 34.9 % then can be determined.

**C. Application of Stiles Method**

In Stiles method, an oil reservoir is visualized as a layered reservoir, with each layer having a different permeability. With the exception of the permeability of the rock and the fluid properties are considered to be the same for all layers.

Calculation procedure is as follows :

- a. Develop capacity distribution of permeability as shown in Table 4, then plot the cumulative capacity versus cumulative thickness, presented in Figure 11. Also generate the parameter of dimensionless permeability as tabulated in Table 5.



**Figure - 10**  
**WOR and recovery relationship**

WOR	Interpolation value	R
1	$R (1 - S_w) = 0.0875$	0.1250
5	$R (1 - 0.72 S_w) = 0.170$	0.2168
25	$R (1 - 0.52 S_w) = 0.265$	0.3140
100	$R (1 - 0.40 S_w) = 0.325$	0.3693

The value  $S_w$  equal to  $S_{wc} = 0.30$



- b. Plot the dimensionless permeability versus cumulative thickness as shown in Figure 11.
- c. Using the dimensionless permeability and cumulative capacity generate the Recovery Factor as shown in Table 6.
- d. Water cut is developed from cumulative capacity and mobility ratio.

Define  $A = Krw/Kro \times \mu_o/\mu_w \times Bo$

where  $Kro$  at  $Swc = 0.635$

$Krw$  at  $Sor = 0.196$

$Bo = 1.11316$

Hence  $A = 1.233$

Use the "A" parameter to determine the water cut as developed in Table 5.

- e. Plot water cut against Recovery Factor as shown in Figure 12.

Maximum water flood oil recovery is defined as,

$$\begin{aligned} \text{Recovery Maximum} &= (Soi - Sor)/Soi \times (Boi/Bo) \\ &= (0.7 - 0.284)/0.7 \times (1.1102/1.1140) \\ &= 0.59 \end{aligned}$$

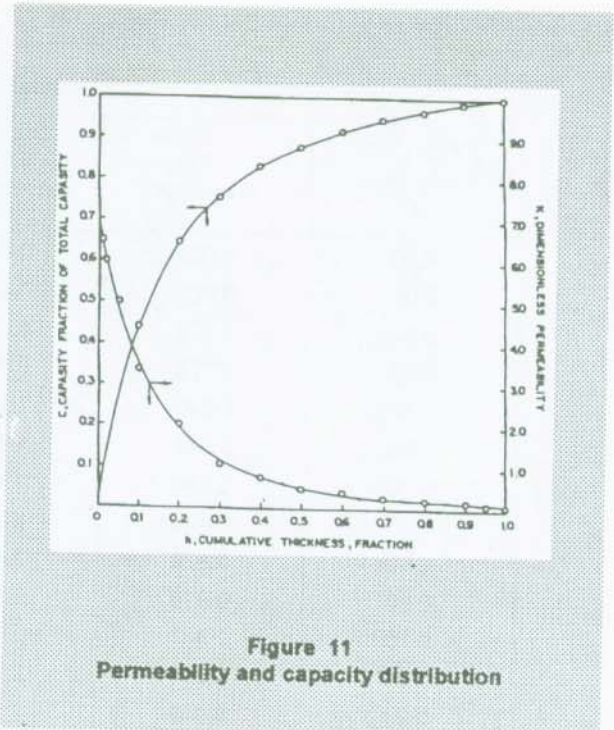


Figure 11  
Permeability and capacity distribution

Table 4  
Capacity distribution (conventional core data)

No.	Thickn. (ft)	Cumul. Thickness (ft)	FracLoF Cum Thickness h	Perm. (mD)	CI Incr. Incr.	CI Incr. of Total Capacity
1.	5	5	0.10	7.92	0.442	0.442
2.	5	10	0.20	3.66	0.204	0.646
3.	5	15	0.30	1.96	0.109	0.755
4.	5	20	0.40	1.34	0.075	0.830
5.	5	25	0.50	0.88	0.049	0.879
6.	5	30	0.60	0.72	0.040	0.919
7.	5	35	0.70	0.50	0.028	0.947
8.	5	40	0.80	0.40	0.022	0.969
9.	5	45	0.90	0.35	0.020	0.989
10.	5	50	1.00	0.16	0.009	1.000
				$\Sigma = 17.90$		



Table 5  
Calculation of water out

Fract. of Cumulation h	C Capacity	C x A (A = 2.782)	C x A + (1-C)	Water cut C x A CxA+(1-C)
0.00	0.000	0.000	1.000	0.000
0.01	0.065	0.182	1.117	0.163
0.02	0.125	0.349	1.224	0.285
0.05	0.275	0.768	1.493	0.514
0.10	0.442	1.235	1.793	0.689
0.20	0.646	1.805	2.159	0.836
0.30	0.755	2.109	2.354	0.896
0.40	0.830	2.319	2.489	0.932
0.50	0.879	2.456	2.577	0.953
0.60	0.919	2.558	2.649	0.969
0.70	0.947	2.648	2.699	0.980
0.80	0.969	2.707	2.738	0.988
0.90	0.989	2.763	2.774	0.996
0.95	0.995	2.780	2.785	0.998
1.0	1.000	2.794	2.794	1.000

Using Figure 12, for a water cut value of 98 % yield a recovery of 88.9 % Hence Recovery Factor =  $88.9 \times 0.59 = 0.5245$  or 52.45 %

#### IV. DISCUSSION THE RESULTS OF ANALYSIS

The initial laboratory investigations in this study tested 10 core samples from non clastic carbonate reservoir from oil fields.

The normalized water-oil relative permeability data used in this study is shown in Figure 1. The results for the fractional flow saturation relationship are presented in Table 1 and Figure 2. Based on this relationship, the water flood displacement performance is calculated as shown in Table 2.

Using a water cut limit of 98 % or oil ratio of 49, the ultimate of water flood water recovery is 43.25 %,

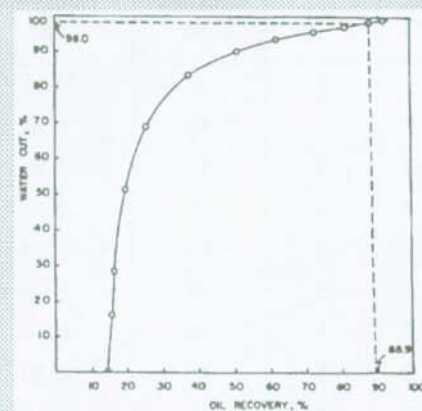


Figure 12  
Water cut versus recovery



Table 6  
Water cut and recovery calculation

Fract. of Cum. thick. h	Dimen.- less permeability K'	Cum. Capacity C	Recovery K'H+ (1-C) K	Water cut CA CA + (1-C)
0.00	7.00	0.000	0.143	0.000
0.01	6.40	0.065	0.156	0.163
0.02	6.00	0.125	0.166	0.285
0.05	4.85	0.275	0.220	0.514
0.10	3.50	0.442	0.259	0.689
0.20	2.00	0.646	0.377	0.836
0.30	1.15	0.755	0.513	0.896
0.40	0.75	0.830	0.572	0.932
0.50	0.52	0.879	0.733	0.953
0.60	0.37	0.919	0.819	0.969
0.70	0.28	0.947	0.889	0.980
0.80	0.24	0.969	0.929	0.988
0.90	0.17	0.989	0.959	0.996
0.95	0.14	0.995	0.986	0.998
1.0	0.10	1.000	1.000	1.000

Notes:  $A = K_{rw}/K_{ro} \times \alpha/w \times B_o$   
 $= (0.196/0.635) \times (2.44686/0.3013) \times 1.1140 = 2.792$

$K_{ro}$  at  $S_{wc} = 0.635$

$K_{rw}$  at  $S_{or} = 0.196$

$\alpha$  at current pressure = 2.44686 cp

$w$  at current pressure = 0.302 cp

$B_o$  at current pressure = 1.1140

equal to a cumulative oil production of 30.40 MSTB as presented in Table 7.

The most optimistic additional oil recovery resulted using the Stiles method, while the most pessimistic value was from the Dykstra-Parson method. The range of water flood recovery was between 34.9 % and 52.45 %. The range of additional recovery over primary recovery was between 10.7 % and 28.2 %.

## V. CONCLUSIONS

1. Based on the method applied, the ultimate oil recovery under water injection is estimated in the

range of 34.9 to 52.4 % of the OOIP. Consequently a water injection scheme could yield additional oil recovery ranging from 7.52 to 19.83 MMSTB.

2. Further properly controlled and documented laboratory data are urgently required before the feasibility of waterflood analysis as a secondary method can be firmly established in oil fields.
3. When deciding whether or not to use waterflooding techniques reliable estimates of recoverable oil have to be made in a comprehensive engineering evaluation in which over all reservoir charac-



**Table 7**  
**Summary of water flood analysis**

Method	Ult. water recovery		Add. recovery due to water flood	
	%	MMSTB	%	MMSTB
Buckley-Leverett	43.25	30.40	19.05	13.39
Dykstra-Parsons	34.90	24.70	10.70	7.52
Stiles	52.45	35.87	28.25	19.86
Crawford				

Notes : Current Recovery (Field Data) = 17 % or 12 MMSTB

teristics are considered in the light of current and anticipated economic factors.

- A more sophisticated way to predict the water flood performance would be a reservoir simulation study which would take into account all factors, such as rate of production, rate of injection, structural position of wells, lateral upward encroachment, shape of the field, etc.

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#### Symbols

- $B_{oi}$  = Initial Oil Volume Factor  
 $B_o$  = Current Oil Volume Factor  
 $ER$  = Fractional Oil Recovery  
 $f_w$  = Fractional Flow of Water  
 $f_w'$  = Fractional Flow as a function of change in the flood front at breakthrough  
 $\bar{K}_j$  = Permeability of 84 % probability  
 $\bar{K}$  = Average Permeability, md  
 $K_{50}$  = Median permeability with 50 % of the permeability being greater or equal to it, md  
 $K_{84.1}$  = Permeability with 84.1 % of the permeability being greater or equal to it, md  
 $K_{ro}$  = Relative Permeability to Oil  
 $K_{rw}$  = Relative Permeability to Water  
 $M$  = Mobility Ratio  
 $Q_i$  = Cumulative Injected Water  
 $RF$  = Recovery Factor  
 $R$  = Maximum Waterflood Recovery  
 $R$  = Recovery Factor  
 $S_w$  = Water Saturation, % PV  
 $\bar{S}_w$  = Average Water Saturation, % PV  
 $S_{wc}$  = Connate Water Saturation, % PV  
 $S_{oi}$  = Initial Oil Saturation, % PV  
 $S_{or}$  = Residual Oil Saturation, % PV  
 $V$  = Permeability Variation  
 $WOR$  = Water-Oil Ratio  
 $WC$  = Water Cut, %  
 $w$  = Viscosity of Water, cp  
 $o$  = Viscosity of Oil, cp. □