The International Journal of Engineering and Science (IJES)
|| Volume || 10 || Issue || 5 || Series I || Pages || PP 48-58|| 2021 ||
ISSN (e): 2319-1813 ISSN (p): 20-24-1805

Safsaf D Oil Reservoir – Oil in Place, Reserves, and Production Performance Estimations

Saleh Ahmed[1], Khalid Elwegaa[2], Mohaned Htawish[3], Haiat Alhaj[4]
[1] Bob L. Herd Department of Petroleum Engineering, Texas Tech University, Lubbock, TX 79409, USA
[2]Department of Petroleum Engineering, Faculty of Engineering, Sabratha University, Libya
[3] Waha Oil Company; Abu Laila Tower, Alkurnish Rd. Tripoli, Libya
[4]Petroleum Engineering Department, Tripoli University, Libya
Corresponding Author: Saleh Ahmed

ABSTRACT
This quantitative study was carried out to estimate the oil initial in place (OIIP) of the Safsaf D oil reservoir using both volumetric methods and a material balance equation. The study also assessed the oil reserves of this field using production Decline Curve Analysis (DCA) method.
Oil initial in place was first estimated using three volumetric methods (Iso-pach method, Pore-volume method and Hydrocarbon pore volume method); furthermore, as these methods rely on mapping, Surfer software was implemented in this study to generate maps. Also, the modified material balance equation of the Havelena and Odeh model was used to estimate the oil initial in place. Field production history, reservoir pressure data, and PVT data were collected for material balance calculations. Finally, field reserves and remaining production life were estimated using exponential decline curve analysis method.
The volumetric methods and the material balance equation are most suitable for OIIP estimation for the Safasf D oil reservoir. OIIP from these methods is about 13.4 MMSTB and 11.67 MMSTB, respectively. In addition, the Safsaf D oil reserves were estimated by exponential decline curve analysis to be approximately 2.78 MMSTB. The results demonstrate that water injection must be continuously used to maintain the reservoir pressure. Furthermore, the infill drilling program is recommended to increase oil recovery.
The history of this field shows that the average water cut is too high (about 93%); therefore, to diminish the high-water production, enhanced oil recovery methods should be considered. Future research using different methods is recommended to validate the oil initial in place and reserves of the Safsaf D oil field.
***KEYWORDS:** - Safsaf D reservoir; volumetric method; material balance equation; decline curve analysis; oil initial in place; reserves*

Date of Submission: 01-05-2021 Date of Acceptance: 15-05-2021

I. INTRODUCTION

Many of the technical elements involved in the calculation of hydrocarbon initial in place and predicting future performance have been studied previously. Consequently, to stress the significance of some tools, three main types of techniques are used to estimate Hydrocarbon Initially in Place (HIIP). Volumetric Methods are "static" methods that estimate HIIP from static properties of the reservoir, including its porosity, thickness, and initial water saturation. The Material Balance Method, in contrast, is a "dynamic" method that estimates HIIP by analyzing historical data on production and pressure. Decline curve analysis that predicts production rates and estimates remaining oil reserves and remaining productive life.

1.1 Volumetric Methods

Volumetric methods of estimating HIIP can be employed immediately after first discovery, before production begins. For this reason, they are the primary tool used for the techno/economic evaluation of oil properties and for the design of field-development projects (Dake, 1978), (Ahmed, 2010), (Craft & Hawkins, 1991).

The accuracy of HIIP estimates calculated using volumetric methods depends significantly on one's understanding of regional geology and on the quality of the seismic analysis, both of which will improve as more wells are drilled and more accurate descriptions and geologic and petrophysical maps of reservoirs become available (Urayet, 2004).

Three different volumetric methods—Iso-Pach, Pore-Volume, and Hydrocarbon Pore Volume are used to estimate OIIP, and they all use the same basic data: petrophysical properties described by well logs, geological maps, and the physical properties of the oil at the initial reservoir conditions.

To estimate OIIP, each of these methods requires mapping. To assist in this mapping, *Surfer* software was used in this study. *Surfer* is a powerful contouring, gridding, and surface-mapping package that interpolates irregularly spaced XYZ data into a regularly spaced grid (Golden Software, 2009).

1.2 Material Balance Equation

Material Balance employ the Single Tank Model, treating reservoir systems as homogeneous units or "blocks." One of the earliest, simplest, and yet most reliable tank models is the Schilthius Tank Model, which is expressed as a Volumetric Material Balance Equation (Dake, 1978), (Craft & Hawkins, 1991), (Fair, 1994), (Ahmed, 2010).
The main assumptions of the Schilthius Tank Model were discussed in detail in the previous research of Safsaf C reservoir (Ahmed, et al., 2019).

Material Balance Calculations are normally run to accomplish the following:

- To validate HIIP estimates obtained using the Static Volumetric Method.
- To identify the driving mechanism affecting the reservoir performance and, for water-drive systems, to identify the aquifer model and the water influx constants.
- To estimate the reserves ultimately recoverable.
- To forecast the ultimate performance of the reservoir.

(Havlena & Odeh, 1963) rearranged the Material Balance Equation into one for a straight line. Their straight-line method requires two variable groups to be plotted against each other, both of which are chosen based on the production mechanism. This study used the straight-line method to estimate the OIIP of the Safsaf D reservoir.

1.3 Decline Curve Analysis

Decline Curve Analysis is a basic tool for predicting production rates and estimating remaining oil reserves and remaining productive life (Cutler, 1924). (Urayet, 2002) reported that calculating reserves—especially in the early life of a reservoir—is the most difficult aspect of reservoir engineering because the only tools available for doing so are macro-analysis techniques that rely on reservoir models in which the characteristics of most points in the reservoir are linear interpolations from known points (i.e. holes that have been drilled). Especially in water-drive systems, reserve values are significantly influenced by variations in permeability (in both the horizontal and vertical directions), layering, pore size, and pore throat size, but such variation is rarely taken into consideration.

The most popular decline curves are those that represent declines in the rate of oil or gas production using Rate-Time Plots. Rate-Cumulative Plots are also popular, however, and plot production rates against cumulative oil or gas production. Both techniques can be applied to single wells, total reservoir, and cumulative production. Three mathematical formulas are used to estimate future production: Hyperbolic Decline, Exponential Decline, and Harmonic Decline (Arps, 1945).

Because it is frequently used for strong water drive reservoirs, Exponential Decline was used in this study to represent or extrapolate the production data of the Safsaf D reservoir.

II. SAFSAF D: BACKGROUND AND RESERVOIR DESCRIPTION

Safsaf field was discovered in 1985 and is in North Africa. The field consists of two reservoirs (C and D). The D block is south of the C block and separated from it by a low-permeability zone. Oil production of Safsaf reservoirs began in 1990 from carbonate Facha member of the Gir formation. Figure (1) demonstrates Safsaf field location map.

Locations of the wells relative to a certain longitudinal system are shown in Figure (2). To date, a total of six wells-3 producers and 3 injectors—have been drilled into the structure D.

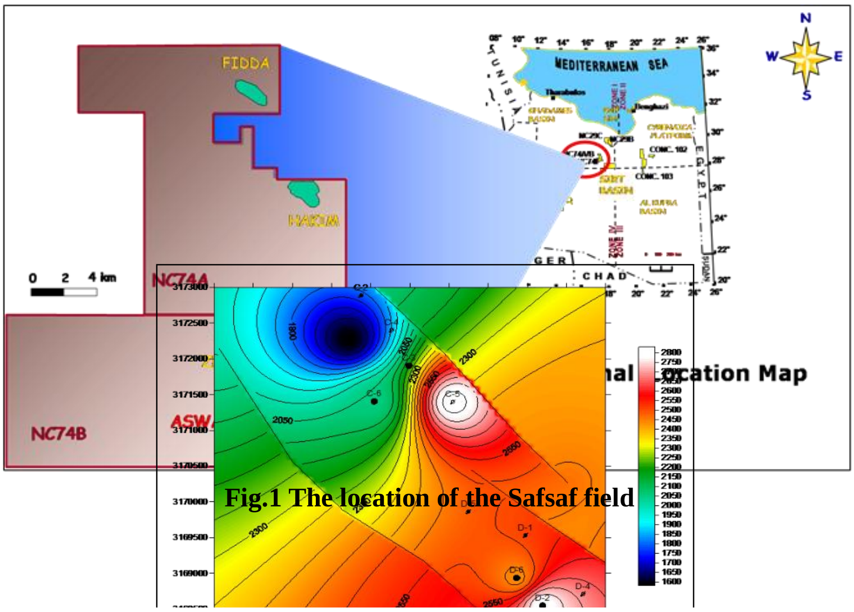

Fig.1 The location of the Safsaf field

Fig. 2 Safsaf field Iso-baric map

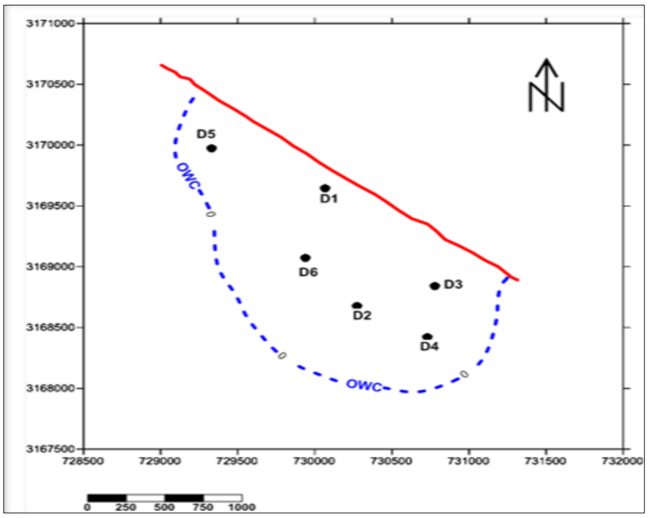

Fig. 3 Map of well locations in Safsaf D

The Safsaf formation is bounded by several faults that trends in a NW-SE direction. all of which are assumed to have small throws such that they may not seal completely. These faults can be seen clearly in the isobaric map of Safsaf formations Figure (3). The reservoir is composed of a series of dolomite and limestone layers separated by tight anhydritic stringers. These anhydrite layers prevent vertical communication between the flow units particularly in the upper parts of the reservoir. Summary of Safsaf D reservoir data are presented in Table (1).

III. CASE STUDY APPLICATIONS

3.1 Volumetric Methods Calculations

Iso-pach method, the Pore-Volume method, and the HPV method are the volumetric methods, which were implemented in this study. The net pay volume (volume of hydrocarbon) was calculated for these volumetric methods using Simpson Rule according to the following equation.

$$V_f = \frac{h}{3}\left[a_0 + 2a_1 + 4a_2 + 2a_3 + 4a_4 + \cdots + 4a_{n-2} + 2a_{n-1} + a_n\right] + \frac{t_n * a_n}{2} \tag{1}$$

where V_f is the net pay volume, h is the contour interval, a_i is the area of contour i, and t_n is the greatest thickness level above the *n*th contour.
In addition to that, *Surfer* software was used to generate the contour maps for all volumetric methods as there rely on mapping. Following equations (2), (3), and (4) represent the original oil in place equations for *the Iso-pach Method, the Hydrocarbon Pore Volume Method, and the Pore Volume Method,* respectively.
The procedure of the calculations of the original oil in place for all the volumetric methods were discussed in detail (Ahmed, et al., 2019)

$$OIIP\ (STB) = \frac{(1-\overline{S_{wi}})V_f\,\overline{\emptyset}}{5.615\,B_{oi}} \tag{2}$$

Table 1 : Safsaf D Reservoir : Data Summary

Formation Depth, (D)	7,200	ft
Avg. Net Pay, (h)	44	ft
Initial Pressure, (P_i)	3,080	Psia
Current Pressure, (P)	2,480	Psia
Reservoir Temperature, (T_{res})	186	°F
Avg. Porosity, ($\phi_{avg.}$)	18	%
Initial Water Saturation, (S_{wi})	28	%
Avg. Permeability, ($k_{avg.}$)	20	md
Saturation Pressure, ($P_{sat.}$)	2,100	Psia
Gas Oil Ratio, (GOR)	1,500	scf/STB
FVF @ Initial Pressure, (B_{oi})	2.28	RB/STB
Oil Viscosity @ Initial Pressure, (μ_o)	0.28	cp
Oil Gravity, (API)	50	°API

$$OIIP\ (STB) = \frac{V_{hydr}}{5.615\,B_{oi}} \tag{3}$$

$$OIIP\ (STB) = \frac{\sum V_i}{5.615\,B_{oi}} \tag{4}$$

3.2 Material Balance Calculations

First, cumulative production and injection history, history of average reservoir pressure, and PVT data of Safsaf D were collected to perform the material balance calculations using Havelena and Odeh model.

- The cumulative production history of the reservoir, i.e. N_p, G_p, and W_p, as well as the cumulative injection data in case of injection projects, i.e. W_i and/or G_{inj} (Table 2).
- The history for average reservoir pressure (Table 2).
- Oil, gas, and water PVT data (Table 3).

The Havelena and Odeh model was built to estimate the OIIP of Safsaf D. The general form of the material balance equation is:

$$N = \frac{N_p\{B_t+(R_p-R_{si})B_g\}+W_pB_w-W_iB_w-G_iB_g-W_e}{(B_t-B_{ti})+mB_{ti}\left(\frac{B_g}{B_{gi}}-1\right)+(1+m)B_{ti}\left(\frac{c_f+c_wS_{wi}}{1-S_{wi}}\right)\Delta_p} \quad (5)$$

Since the Safsaf D reservoir is above the bubble-point pressure, no water influx, and gas injection, the above equation can be written as follows:

$$N = \frac{N_pB_o+W_pB_w-W_i}{(B_o-B_{oi})+B_{oi}\left[\frac{c_f+c_wS_{wi}}{1-S_{wi}}\right]\Delta_p} \quad (6)$$

Table 2: Reservoir pressure and production history for Safsaf D

Date	Pressure psi	Cum. Oil MMSTB	Cum. Gas MMscf	Cum. WTR MMSTB	Cum. Gas MMscf	Cum WTR Inj. MMSTB
6/30/1990	3,080	0.0000	0.0000	0.0000	0	0.0000
8/31/1990	2,788	0.1114	248.2540	0.0160	0	0.0000
9/30/1990	2,752	0.1162	259.1870	0.0161	0	0.0000
10/31/1990	2,716	0.1446	325.9836	0.0161	0	0.0000
11/30/1990	2,682	0.1660	368.8494	0.0161	0	0.0000
12/31/1990	2,648	0.1895	399.5187	0.0161	0	0.0097
3/31/1991	2,558	0.3038	563.5896	0.0218	0	0.1182
7/31/1991	2,453	0.4997	992.0958	0.0511	0	0.3086
1/31/1992	2,326	0.7424	1502.5125	0.0900	0	0.6240
6/30/1992	2,249	0.8406	1706.9603	0.0931	0	0.8661
9/30/1992	2,212	0.9020	1852.0666	0.0933	0	1.0609
7/31/1993	2,142	1.0430	2131.6348	0.0987	0	1.6019
10/31/1993	2,134	1.1049	2273.5128	0.1019	0	1.7312
12/31/1993	2,132	1.1413	2377.9037	0.1128	0	1.8037
4/30/1994	2,135	1.1927	2510.8794	0.1225	0	1.9906
10/31/1994	2,153	1.2520	2669.5224	0.1596	0	2.4536
3/31/1995	2,186	1.3076	2812.2092	0.1904	0	2.8113

Table 3: PVT data for Safsaf D

Pressure psi	Relative Volume of Oil and Gas, (v/v_{sat})	Viscosity of Oil, (cp) @ 202 °F	GOR (Liberated per Barrel of Residual Oil)	GOR (In Solution per Barrel of Residual Oil)	Oil FVF (Bbl/STB)
5,000	0.9063	0.32			3.080
4,490	0.9169	0.31			3.116
3,995	0.9291	0.31			3.157
3,519	0.9426	0.30			3.203
2,994	0.9595	0.29			3.260
2,200	0.9948	0.28			3.380
BP=2,108	**1.0000**	**0.27**	**0**	**3,231**	**3.398**
1,873	1.0963	0.28	506	2,725	3.064
1,503	1.3511	0.29	1,150	2,081	2.692
1,051	2.0108	0.31	1,694	1,537	2.354
627		0.34	2,138	1,093	2.079
203		0.37	2,738	493	1.659
15		0.82	3,231	0	1.075

From equation (6), the following equations can be written as:

$$F = N_p B_o + W_p B_w - W_i \quad (7)$$

$$E_o = B_o - B_{oi} \quad (8)$$

$$E_{f,w} = B_{oi}\left(\frac{c_f + c_w S_{wi}}{1 - S_{wi}}\right)\Delta_p \quad (9)$$

where F represent total production volume minus the total injected volume (bbls), E_o represents the expansion of oil and its originally dissolved gas (bbls/stb), and $E_{f,w}$ represents the expansion of the initial water and the reduction in the pore volume (bbls/stb).

Then, equations 7, 8, and 9 were used to plot F versus $E_o + E_{f,w}$ to estimate the OIIP using the straight-line method of MBE,

3.3 Production Forecast via Decline Curve Analysis

In this study, Decline Curve Analysis was used to determine total reserves, remaining reserves, and abandonment time of Safsaf D reservoir after identifying the decline type, the decline factor, and the initial decline rate according to the production history of the reservoir.

The exponential decline formula was selected to extrapolate the production data for the Safsaf D reservoir. The general form of the DCA is given in equation (10)

$$\frac{q}{dq/dt} = -bt - \frac{1}{a_i} \quad (10)$$

where q is the production rate at any time, t represents the time from the start of production decline, a_i is a decline factor representing the initial rate of decline, and b is a reservoir constant that ranges between 0 and 1.0. For strong-water drive reservoirs, the value of b is generally very near to 0. so, equation (10) can be written in the following form. The decline period from 31st of May 2004 to 28th of February 2011 was selected to apply the Exponential decline.

$$\left(\frac{q}{dq/dt}\right) = -\frac{1}{a_i} \quad (11)$$

IV. RESULTS AND DISCUSSION

4.1 Volumetric Methods Results

The results for average porosity, average water saturation, and net pay thickness for each well are presented in Table 4. Contour intervals for all volumetric methods were obtained using surfer software.

Table 4: Average properties of the Safsaf D reservoir

Well #	Net Pay ft	Avg. Porosity %	Avg. WTR Sat. %	Isopach Map ft-Interval	Pore Vol. Map ft-Interval	H.C. Map ft-Interval	$\phi \times h$	$S_{wi} \times h$
D1	72	21.86	22.89	72	15.74	12.14	1,573.92	1,648.08
D2	33	19.93	20.85	33	6.58	5.21	657.69	688.05
D3	31.5	19.83	23.40	31.5	6.25	4.78	624.65	737.10
D4	36	19.95	30.05	36	7.18	5.02	718.20	1,081.80
D5	11	21.73	50.22	11	2.39	1.19	239.03	552.42
D6	40	21.56	22.85	40	8.62	6.65	862.40	914.00
Sum:	223.5	124.86	170.26				4,675.89	5,621.45

Table 4 also shows, the average porosity (20.92%) and average water saturation (25.15%) of the reservoir, which were calculated using the thickness-weight method. The results revealed that well D1 has the highest contour interval where as well D5 has the lowest contour interval using all volumetric methods.

4.1.1 The Iso-Pach Method Results

Figure 4 shows the iso-pach map of the Safsaf D reservoir built using *Surfer*. The productive area was estimated from the map using planimeter. Then, the net pay volume and OIIP were calculated (Table 5).

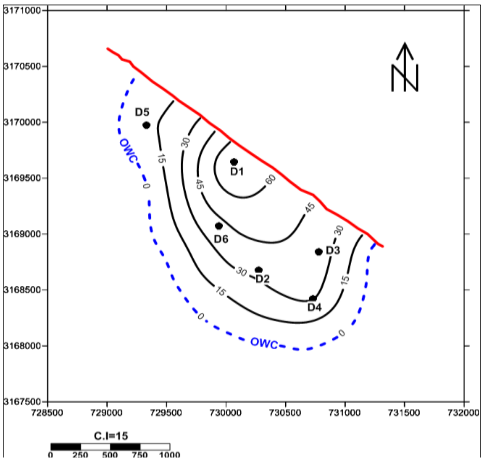

Fig. 4 Iso-pach map of the Safsaf D reservoir

Table 5: Calculations and results for the Iso-pach method

Productive Area	Planimeter Area, cm^2	Area, acre	Ratio of Areas, unitless	Interval (h), ft	Interval * Ratio	ΔV Acre-ft
A_0	71.00	924.88	#	#	#	#
A_1	45.25	589.45	0.64	15	9.56	11,357
A_2	31.50	410.33	0.70	15	10.44	7,498
A_3	14.25	185.63	0.45	15	6.79	4,360
A_4	4.25	55.36	0.30	15	4.47	1,712
A_5	0.00	0.00	0.00	12	0.00	221
Sum				72.0		**V_r = 25,149**
OIIP = 13.40 MMSTB						

4.1.2 The Hydrocarbon Pore Volume Method Results

Surfer was used to build a map for Hydrocarbon pore volume (Figure 5) and depending on that, the hydrocarbon pore volume was calculated for each well. Finally, total HPV and OIIP were calculated (Table 6).

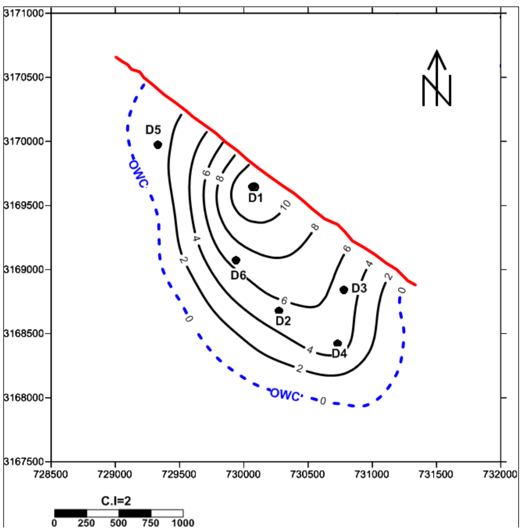

Fig. 5 Map of hydrocarbon pore volume for the Safsaf D reservoir

Table 6: Calculations and results for the map of Hydrocarbon pore volume

Productive Area	Planimeter Area, cm^2	Area, acre	Ratio of Areas, unitless	Interval (h), ft	Interval * Ratio	ΔV Acre-ft
A_0	71.00	924.88	#	#	#	#
A_1	48.00	625.27	0.68	2.00	1.35	1,550
A_2	33.00	429.87	0.69	2.00	1.38	1,055
A_3	20.00	260.53	0.61	2.00	1.21	690
A_4	10.25	133.52	0.51	2.00	1.03	394
A_5	3.50	45.59	0.34	2.00	0.68	171
A_6	0.50	6.51	0.14	2.00	0.29	46
A7	0.00	0.00	0.00	0.86	0.00	2
Sum				8.36		**V_{hydr} = 3,910**
OIIP = 13.30 MMSTB						

4.1.3 The Pore Volume Method Results

Like the previous methods, *Surfer* was used to build the pore volume map (Figure 6). The initial hydrocarbon volume for each grid square of the map for pole volume was calculated from porosity, oil saturation, and thickness data obtained from iso-maps. Then, the total hydrocarbon volume and the OIIP were estimated (Table 7).

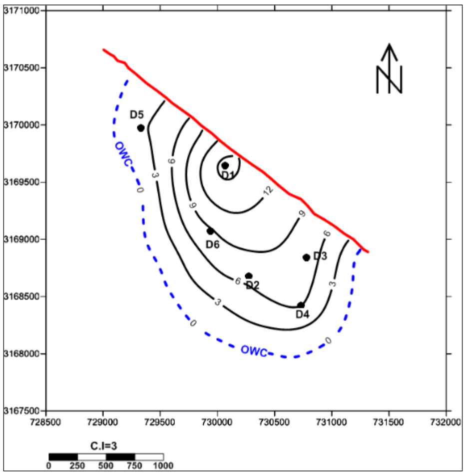

Fig. 6 Pore volume map of the Safsaf D reservoir

Table 7: Calculations and results for the Pore volume method

Productive Area	Planimeter Area, cm^2	Area, acre	Ratio of Areas, unitless	Interval (h), ft	Interval * Ratio	ΔV Acre-ft
A_0	71.00	924.88	#	#	#	#
A_1	47.00	612.24	0.66	3.00	1.99	2,306
A_2	31.25	407.08	0.66	3.00	1.99	1,529
A_3	16.00	208.42	0.51	3.00	1.54	923
A_4	6.50	84.67	0.41	3.00	1.22	426
A_5	0.75	9.77	0.12	3.00	0.35	123
A_6	0.00	0.00	0.00	0.74	0.00	2
Sum				15.74		**V_i = 5,309**
OIIP = 13.52 MMSTB						

Although the three volumetric methods employed different calculations, the results revealed that the values they yielded for OIIP were almost identical, ranging between 13.30 and 13.52 MMSTB.

4.2 Material Balance Results

The following results (shown in Table 8) were obtained by applying the straight-line formulation of the material balance equation and using the production history, pressure history, and PVT data of Safsaf D.

Table 8: Results for material balance for the Safsaf D reservoir

Bo Bbl/STB	N MMSTB	F MMSTB	E_o Bbl/STB	$E_{f,w}$ Bbl/STB	$E_o + E_{f,w}$ Bbl/STB
2.7292	0.00	0.00	0.00	0.0000	0.0000
2.7616	8.69	0.32	0.0324	0.0048	0.0372
2.7658	8.03	0.34	0.0366	0.0054	0.0420
2.7701	8.89	0.42	0.0409	0.0060	0.0469
2.7740	9.27	0.48	0.0448	0.0066	0.0514
2.7780	9.51	0.53	0.0488	0.0071	0.0560
2.7890	10.97	0.75	0.0598	0.0086	0.0684
2.8022	13.71	1.14	0.0730	0.0103	0.0833
2.8185	15.32	1.56	0.0893	0.0124	0.1017
2.8287	14.17	1.60	0.0995	0.0137	0.1132
2.8336	13.38	1.59	0.1044	0.0143	0.1187
2.8431	11.30	1.46	0.1139	0.0155	0.1293
2.8441	11.59	1.51	0.1149	0.0156	0.1305
2.8444	11.88	1.56	0.1152	0.0156	0.1308
2.8441	11.67	1.52	0.1149	0.0156	0.1305
2.8416	9.89	1.26	0.1124	0.0153	0.1277
2.8372	8.87	1.09	0.1080	0.0147	0.1227
2.7616	8.69	0.32	0.0324	0.0048	0.0372

Data in Table 8 were plotted as shown in Figure 7 (F vs. $E_o + E_{f,w}$), and the OIIP of Safsaf D was found to be 11.67 MMSTB when the straight-line formulation of MBE was used.

The following table 9 shows, the three volumeric methods yielded OIIP values that were very nearly the same, where as OIIP resulted from material balance equation was approximatly 2 MMSTB less than OIIP resulted from volumetric methods.

Table 9: A comparison of the OIIP results for the Safsaf D reservoir

No.	Method	OIIP (N), MMSTB
1.	Iso-pach	13.40
2.	Pore volume	13.52
3.	Hydrocarbon pore volume	13.30
4.	Material balance equation	11.67

4.3 Results for the Decline Curve Analysis

As explained, Exponential Decline was applied to the production history of Safsaf D to estimate its total and remaining reserves. The analysis considered the period from 31st of May 2004 to 28th of February 2011.
Table 10 shows the results of the decline curve analysis for this period, and Figure 8 shows the match between the production history and the data obtained by using exponential decline and the oil production forecast for the Safsaf D reservoir, which included a final rate of 20 BPD in March 2015.

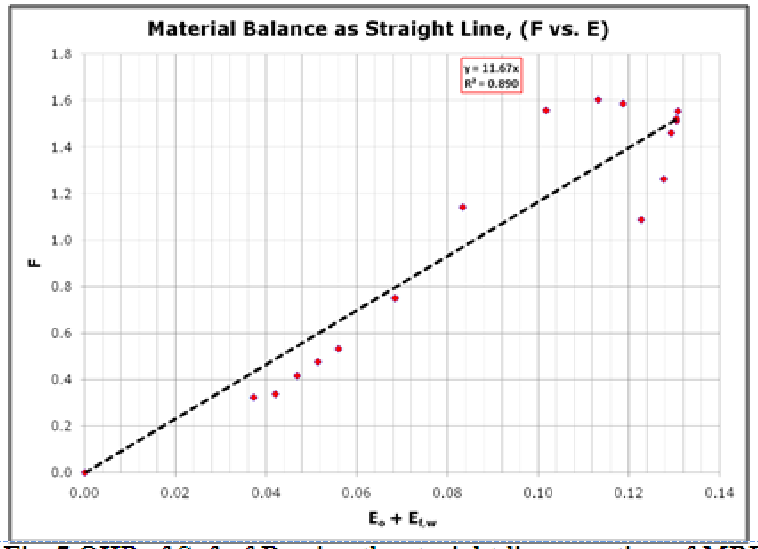

Fig. 7 OIIP of Safsaf D using the straight-line equation of MBE.

Table 10: Results of the production decline analysis for the first period of the Safsaf D reservoir

Period	From	To
	5/31/2004	2/28/2011
# of Points	82	
b	0.05	
q_i, BPD	339	
a_i, 1/year	0.286305	
q cal. at end of Period, BPD	54	
Np at end of Period, BBL	2,772,966	
Assumed q_e, BPD	15	
Remaining Reserves, BBL	55,503	
Total Reserves, BBL	2,778,469	

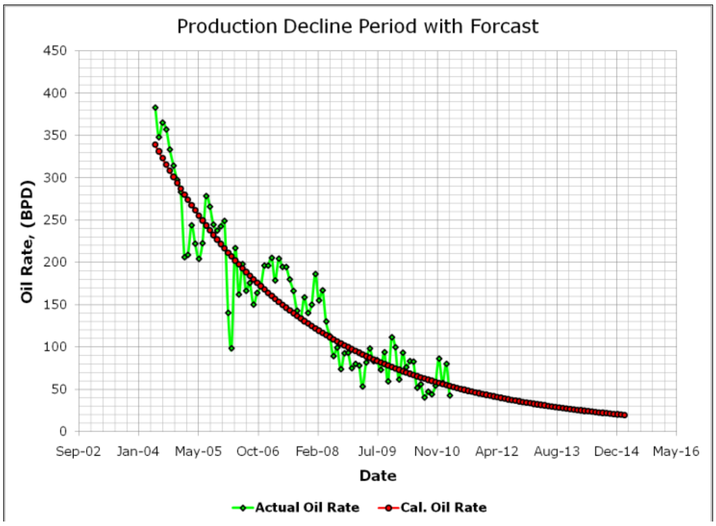

Fig. 8 The production period with forecast of the Safsaf D reservoir

To better interpret and analyze the Safsaf D production, the production history and decline production period were combined as shown in Figure 9. Doing so revealed that an increase in production occurred at the beginning of the selected decline period due to workover operation of wells D2, D3, and D6 at the end of 2004 and the early of 2005.

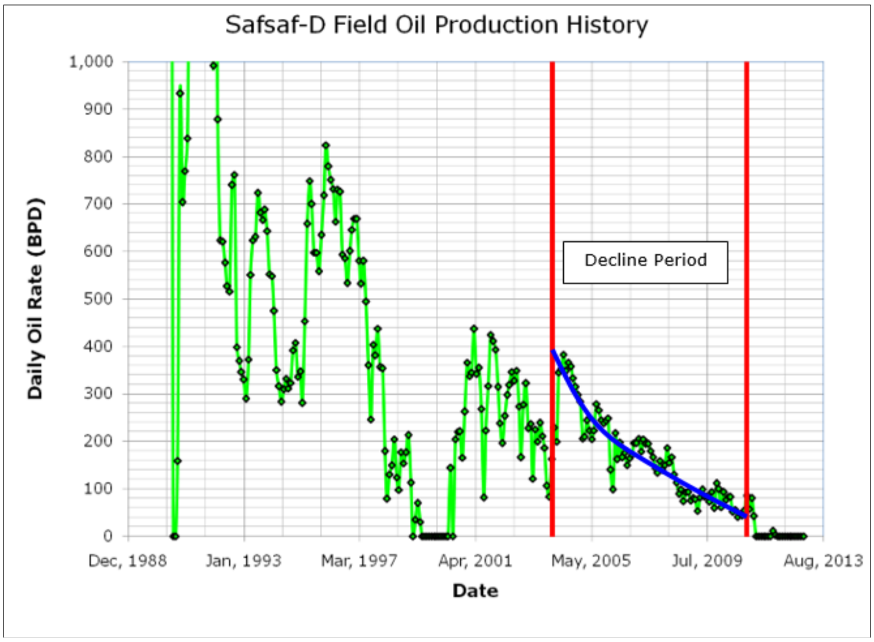

Fig. 9 Production history of Safsaf D and a decline curve analysis period

V. CONCLUSIONS

Oil production from Safsaf D reservoir started in May 1990 with initial average oil production rate of 1,314 BOPD and the peak oil production in July 1990. The reservoir is volumetrically undersaturated and significant drops in pressure have been detected, and water injection to maintain pressure was initiated in December 1990. This study estimated the OIIP of Safsaf D using various volumetric methods and the straight-line formulation of the material balance equation. It also estimated the total and remaining reserves using the exponential method of decline curve analysis.

1. OIIP was estimated using volumetric methods that utilized Isopach, pore volume, and H.C. pore volume maps. The OIIP values ranged from 13.30 to 13.52 MMSTB.
2. OIIP was also estimated using the straight-line formulation of the material balance equation. the value for OIIP was 11.67 MMSTB, which is approximately less than by 2 MMSTB of those resulted from volumetric methods.
3. Total reserves were estimated using a normal Decline Curve Analysis, and the results showed a value 2.77 MMSTB.
4. The study revealed that the reservoir can be developed by using infill drilling and continuing water injection to maintain reservoir pressure.
5. To diminish the high-water production, appropriate enhanced oil recovery method should be considered as the average reservoir water cut is too high (about 93%).

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