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Screening of Libyan EOR Candidates (Applying MMP and MMC Criteria)

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مسح لحقول النفط الليبية المرشحة لطرق الاسترداد الإضافي باستخدام معيار الضغط الأدنى للامتزاجية والمركبات الأدنى للامتزاجية

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إن كفاءة أو فاعلية طرق الاسترداد الإضافي وخاصة الطرق التي تشمل برامج الحقن بالغاز تتحكم فيها بشكل هام خواص موائع المكمن وكذلك درجة الحرارة والضغط. كما تسيطر عوامل أخرى مثل خواص صخور المكمن والقوة الدافعة في النجاح النهائي لتقنيات الاسترداد الإضافي. وقد تم في هذا العمل التركيز على تأثير خواص موائع المكمن فقط.

تم في هذه الدراسة تسليط الضوء على الأسئلة الأربعة التالية:

1 – ما هو الضغط الأدنى للمكمن الذي يكون عنده مائع المكمن قابل للامتزاج مع ثاني أكسيد الكربون؟ (طريقة الغمر بثاني أكسيد الكربون).

2 – ما هو الضغط الأدنى الذي يصبح عنده غاز الحقل قابل للامتزاجية مع سائل المكمن؟ (طريقة الغمر للامتزاجية بالتبخر الهيدروكربوني).

3 – في حالة عدم توفر إمكانية تشغيل المكمن عند أو أعلى من الضغط اللازم للحصول على الامتزاجية بالإتصال المتعدد مع ثاني أكسيد الكربون، هل يعد الحقن باستخدام ثاني أكسيد الكربون مثمر؟ (الغمر غير القابل للامتزاجية، باستخدام ثاني أكسيد الكربون).

4 – ما هو المائع المشبع المتبقي – مثل مكثفات الغاز المسال – وما هي الكمية المطلوبة إضافتها لغاز الحقل لحدوث الامتزاجية مع مائع المكمن عند درجة الحرارة والضغط الحالي؟ (الغمر عن طريق الامتزاجية بواسطة التكثيف الهيدروكربوني).

للإجابة على الأسئلة المشار إليها أعلاه يمكن استخدام عدة تقنيات إعتماداً على البيانات المتوفرة. فكلما كانت المعلومات أكثر إتاحة كلما قلّت درجة الغموض في إجاباتنا التي نقدمها.

تم في هذا العمل إستعمال العلاقات الرياضية المتوفرة للإجابة على الأسئلة سالفة الذكر، كما تم أيضاً مقارنة النتائج المتحصل عليها (باستخدام هذه العلاقات) ببعض بيانات التجارب المعملية.

هذا بالإضافة إلى توصية بضرورة إنتاج أفضل الطرق للقيام بعملية المسح.

Abstract: *The performance of the EOR methods, particularly those involving gas injection schemes, is governed significantly by the reservoir fluid properties and the reservoir temperature and pressure. Other factors like reservoir rock properties and the drive energy also control the ultimate success of the EOR technique. However, in this work, we concentrate on the influence of the properties of the reservoir fluids only.*

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We have also focused our attention on the following four questions:

1. *What is the minimum reservoir pressure at which the reservoir fluid will be miscible with CO_2? (miscible CO_2 flood.)*
2. *What is the minimum pressure at which field gas will become miscible with the reservoir fluid? (vaporising hydrocarbon miscible gas flood.)*
3. *If the reservoir can not be operated at or above the pressure required for achieving multiple contact miscibility with CO_2, could injection of CO_2 still be beneficial? (Immiscible CO_2 flood.)*
4. *What rich fluid stock – like LPG condensate – and how much of it has to be added to field gas to make it miscible with the reservoir fluid at the existing pressure and temperature? (condensing hydrocarbon miscible gas flood.)*

Depending on the information available, several techniques can be used to answer the questions raised above. Naturally, the more information we have at hand, the less will be the degree of uncertainty in the answers we provide. In this work, we have utilized the empirical correlations available in the literature to answer the questions. We have also compared the answers we obtained by the application of these correlations with some experimental data already generated in the laboratories. Based on these, we plan to recommend the best way to carry out the screening process.

INTRODUCTION

The search for tomorrow's oil reserves has directed the efforts of the energy industry to frontiers beyond the conventional exploration and production strategies. This is what is called the enhanced oil recovery (EOR). The results of successful application of this new technology will have a decisive impact on the energy conservation programme of any country.

The first step in formulating an EOR programme is to screen the reservoir using criteria based on past experience. This is done to select one or more possible techniques that are further investigated in more detail. During the last decade, several empirical correlations have been developed to help screen the reservoirs.

Here in Al Jamahiriya (GSPLAJ) a preliminary screening has been carried out using the initial oil in place (IOIP>500 MMSTB) as a first screening criterion to arrive at a preliminary list of 30 possible EOR candidates (Table, 1). Most of these are likely to be economical candidates for application of EOR by gas (CO_2 hydrocarbon and/or N_2 injector).

During 1986, the EOR department of National Oil Corporation (ONC) developed a set of guidelines for the implementation of EOR schemes in the GSPLAJ. These guidelines were drawn based on world-wide experience. Based on the guidelines, the operating companies have initiated several projects mainly concerned with the data gathering required for these schemes. In particular, they are concerned with experimental data generated in the laboratories. In some cases, field data generation, particularly determination of residual oil saturation, has also been initiated. The experimental data being generated by the operating companies consists mainly of reservoir fluid compositions, miscibility limits and core floods. Data is being generated for possible application of miscible or immiscible CO_2 floods and miscible hydrocarbon floods.

Since 1986, the EOR department has carried out two major projects[1,5] which are of particular importance to the selection of the optimum gas injection scheme. The first work is concerned with the compilation of all data pertaining to the gas reserves and their compositions. The gases considered were hydrocarbon gases from associated and non-associated sources and CO_2. The second major work involved the ongoing studies on technical and EOR planning. Part of the work involved the detailed study of the behavior of reservoir fluids of chosen reservoirs. The expertise gained in these two studies enabled us to review the guidelines formulated by the department with particular emphasis on Libyan oils. The present work is one such outcome of this endeavor.

CO_2 injection is known to improve recovery by several mechanisms. These include the generation of miscibility by multiple contact and the reduction of viscosity and the swelling of the oil volume by dissolution. Reduction in the viscosity of the oil will lead to improved mobility ratio which, in turn, can lead to improvement in the vertical and areal sweeps and increased displacement efficiencies. Swelling of the oil will lead to reduction in the amount of oil left behind in the reservoir for the same liquid saturation. Both these factors can improve the performance of the reservoir if the CO_2 injection is followed by water flood.

Except for reservoirs at high pressure, miscible hydrocarbon flood is realized by a condensing drive mechanism. The gas that will achieve this has to be fairly rich in its propane/butane content. Field gases seldom contain these components in sufficient amounts. It is then usually necessary to blend the field gases with rich fluids like LPG to enable them to achieve miscibility with the reservoir fluid.

The objectives of the study are summarized as follows:

1. To determine the miscibility limits for the reservoir fluids with CO_2 and hydrocarbon gases (vaporizing and condensing drives).
2. To determine the swelling factor and viscosity reduction for immiscible CO_2 injection.
3. Based on 1 and 2, the recommended EOR schemes that will warrant further investigations for the reservoirs, will be decided, and the current EOR programme of the operating companies, in the light of the results generated herein, will be reviewed.
4. The best method to screen reservoir fluid data, to evaluate the feasibility of gas injection schemes, will be recommended.

METHODOLOGY

The detailed compositional analysis of all the reservoir fluids was collected from the PVT reports. This information was input into the empirical correlations listed below to generate the required miscible limits. The empirical correlations used are:

CO_2 MMP Limit

Holm and Josendal, 1974 modified by Mungan, 1981[9]
Cronquist, 1978[10]
Petroleum Recovery Institute, 1979[11]
Yellig and Metcalf, 1980[7]
Johnsons and Pollin, 1981[8]
Alston, 1985[12]
Glaso, 1985[14]
Eakin and Mitch, 1988[15]

Hydrocarbon Vaporising Drive

Glaso, 1985[14]
Glaso, 1990[16]
Firoozabadi and Aziz, 1986[17]

Hydrocarbon Condensing Drive

Benham *et al*, 1960[13]
Glaso, 1985[14]

Immiscible CO_2 Drive

Simon and Graue, 1965[18]

The results generated by these different correlations were analysed for their consistency using statistical methods. They were also compared with the experimental data available. Based on these, a limited number of these correlations was chosen to evaluate the feasibility of the processes.

The results generated, using these correlations, were then compared to other available data from the reservoir to decide on the feasibility of the different gas injection schemes.

RESULTS

The Holm, Josendal and Mungan, Yellig-Metcalfe, Glaso, and Eakin-Mitch correlations perform better than the others for CO_2 MMP prediction.

There is good agreement between the predictions made for rich gas miscibility limits using the correlations of Benham *et al.* and Glaso. Any one of them can be used for screening purposes.

There is poor agreement in the predictions made for vaporizing hydrocarbon miscibility limits using the correlations of Firoozabadi and Aziz and those of Glaso. Since not much experimental data is available it is not possible to assess their relative merits. However, the correlations of Firoozabadi and Aziz were developed based on results with lean hydrocarbon gas. Glaso developed his correlation based on results with nitrogen gas. In this study, we are mainly concerned with the feasibility of using lean gas for EOR. Hence, the correlations of Firoozabadi and Aziz were used for the screening purpose.

Miscible CO_2 flood is feasible in 20 out of the 26 candidates. Abu Attiffel appears to be suitable for CO_2 flood and hydrocarbon vaporizing gas flood using field gas.

Out of the remaining six candidate reservoirs, only Ragubat and Kotlat are suitable for enriched gas injection.

The immiscible CO_2 flood appears attractive in three of the four remaining shallow reservoirs (Bahi PL-7, Gialo Eocene and Dahra PL-7/YPL-7).

No EOR process involving gas injection appears suitable for Dahra-Hofra PL-5 reservoir unit.

Good consistency exists between the operating companies (OPCO's) EOR programme and the results of this study.

DISCUSSION

Database

The database consists of the detailed compositions of reservoir fluids. The pertinent data are summarized in Table 1 with a wide range of PVT properties as summarized in Table 2.

Table 1. Reservoir fluid compositions and properties of Libyan EOR candidates.

Component	Sarir C-Main	Sarir C-North	Sarir L	Messla	N.A..U (TBG))	N.A.U (BAM)	Haram	Kotla	Nasser North	Nasser South		Raguba	Jebel	LDM	Bahi PL7	Dahra-Jofra PL5
N_2	1.050	0.740	1.03	1.760	1.520	1.420	0.920	1.140	0.830	0.600	0.400	0.620	0.290	0.980	0.200	0.110
CO_2	1.120	1.150	0.74	1.240	0.590	1.150	0.800	0.000	1.920	1.510	1.340	1.080	1.410	3.920	.420	0.520
H_2S	0.000	0.000	0.00	0.000	0.000	0.000	0.000	0.000	0.210	0.940	0.650	0.000	0.000	0.000	0.390	0.380
C1	10.820	5.580	4.32	17.710	37.290	38.850	10.480	13.323.	29.610	22.050	18.770	32.510	42.020	49.040	4.350	18.550
C2	4.340	3.180	3.00	7.530	5.420	5.240	2.540	290	10.680	10.760	8.720	10.580	7.440	9.260	3.750	6.990
C3	8.220	4.960	3.55	8.470	4.510	4.300	2.180	6.050	7.280	7.610	5.540	7.520	6.640	5.520	9.260	6.560
C4	8.630	4.650	5.45	7.520	4.540	4.250	2.770	7.000	5.260	5.980	4.440	6.730	5.390	4.550	11.610	7.890
C5	6.400	6.230	6.56	5.100	2.670	3.290	2.720	6.050	3.470	3.540	4.040	5.200	3.990	3.220	9.890	6.700
C6	4.450	6.580	6.25	3.980	3.570	3.300	2.470	4.910	5.330	1.920	4.290	4.410	3.840	3.010	7.130	6.200
C7+	54.970	66.930	69.11	46.690	39.890	38.200	75.120	58.240	35.410	45.090	51.810	31.350	28.980	20.500	53.000	46.100
M.Wt C7+	290	208	210	230	310	308	382	281	214	227	222	201	227	179	195	188
API C7+	32	-	-	36	33	33	22	27	0	36	37	38	34	46	38	39
Oil API gravity	37	40	41	37	34	33	23	32	38	38	37	40	36	50	44	44
PI (psig)	3.909	3.906	4.006	3.970	4.272	4.695	2.012	2.450	2.457	2.457	2.457	2.385	3.375	4.028	1.188	959
Pb (psig)	715	500	544	1.320	3.530	2.790	540	545	2.060	1.395	1.178	2.385	3.310	3.780	222	942
Temp (deg F)	225	230	240	238	230	240	184	164	170	170	178	214	206	262	150	129
Pb density (gm/cc)	0.749	0.745	0.756	0.699	0.716	0.711	0.853	0.790	0.695	0.717	0.735	0.629	0.635	0.507	0.762	0.712
Pb viscosity (cp)	1.120	2.050	0.610	0.713	1.010	1.010	15.690	2.040	0.550	0.620	0.800	0.350	0.310	0.115	1.010	0.600
Pb FVF (RB/STB)	1.232	1.170	1.175	1.456	1.344	1.370	1.094	1.141	1.377	1.335	1.256	1.680	1.710	2.320	1.140	1.278
Diff. Initial GOR (SCF/STB)	192	167	187	460	498	551	78	160	775	528	370	1036	1090	1971	200	427

Component	Samah	Waha North	Waha South	Defa	Gialo Eocene	Gialo Pale.	Dahra PI7/YPL7	Amal B	Amal E	Amal N	Gahni L-Earrud	Zenad Earrud	Intisar-D	Abu-Attifel Main
N_2	0.710	0.520	0.510	1.390	0.310	0.480	0.760	1.250	0.980	1.560	0.000	0.150	0.000	0.240
CO_2	0.600	0.200	0.140	0.280	1.420	0.970	1.270	0.700	0.900	0.800	2.100	0.270	1.350	3.365
H_2S	0.000	0.000	0.000	0.000	0.490	0.170	2.100	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C1	8.080	17.320	23.060	21.320	1.470	14.620	5.290	26.900	35.790	29.720	33.810	29.720	33.550	58.952
C2	2.230	6.920	6.930	6.210	2.110	6.750	5.120	6.970	7.590	7.670	8.030	6.420	5.350	9.044
C3	3.780	9.460	8.610	8.110	2.930	6.410	3.010	6.800	6.920	6.740	8.900	7.350	4.410	3.138
C4	3/800	7.030	6.400	6.370	4.670	7.500	5.810	6.370	5.600	5.890	7.310	5.490	4.650	2.005
C5	3.510	5.010	4.530	3.840	6.280	5.620	7.300	4.650	4.160	4.140	4.910	4.450	3.654	1.444
C6	3.580	4.420	4..120	5.450	5.900	5.020	4.590	4.340	2.840	3.980	2.910	3.880	5.006	1.630
C7+	73.710	49.120	45.700	47.030	74.420	52.460	64.750	42.120	34.220	39.500	32.030	42.270	42.080	20.784
M.Wt C7+	247	226	227	257	234	222	198	261	262	262	201	202	219	244
API C7+	34	34	34	31	35	36	35	34	35	-	36	-	-	-
Oil API gravity	35	35	35	36	38	39	39	35	38	37	38	37	39	42
PI (psig)	2.705	2.983	2.963	2.490	1.176	2.726	1.129	4.875	4.675	4.675	2.340	2.385	4.257	6.868
Pb (psig)	536	1.075	1.400	1.204	137	910	398	1.921	2.639	2.185	2.093	1.717	2.225	5.746
Temp (deg F)	214	180	180	156	125	209	146	220	234	239	170	180	226	300
Pb density(gm/Co)	0.767	0.733	0.725	0.745	0.796	0.722	0.766	0.707	0.676	0.689	0.669	0.688	0.677	0.585
Pb viscosity (cp)	1.290	0.840	0.800	0.992	2.380	0.680	1.180	0.840	0.555	0.590	0.320	0.590	0.460	0.460
Pb FVF (RB/STB)	1.158	1.315	1.344	1.255	1.067	1.315	1.140	1.393	1.520	1.448	1.603	1.472	1.460	2.009
Diff. Initial GOR (SCF/STB)	133	420	488	352	48	381	149	537	750	602	980	713	525	1.747

Table 2 . Range of PVT data.

	Minimum	Maximum
API of oil	23	50
Temperature, deg F	125	300
Initial GOR, scf/stb	49	1972
Mwt of C7+	179	382
Mwt of C5+	156	363

Evaluation of the Correlations

A. CO_2 MMP

Figure 1 shows the predictions of the correlations. The ordinate is the value of the MMP predicted while the abscissa is the average of the MMPs predicted by the eight correlations. There is a wide scatter in the results. Predicted MMPs vary by as much as 1000 psi from the average values predicted by the correlations. On the basis of this information alone, it was not possible to choose the appropriate correlation for the screening work.

Figure 2 shows the plot of the experimental MMP for these reservoir fluids against the MMP predicted by the correlations. The correlations of Holm, Josendal and Mangan, Yellig-Metcalfe, Glaso, and Eakin-Mitch performed better than others. The predictions deviated from the experimental results by about 400 psi. The standard deviations of these correlations were 16, 13, 17 and 17% respectively. The complete data are given in Table 3.

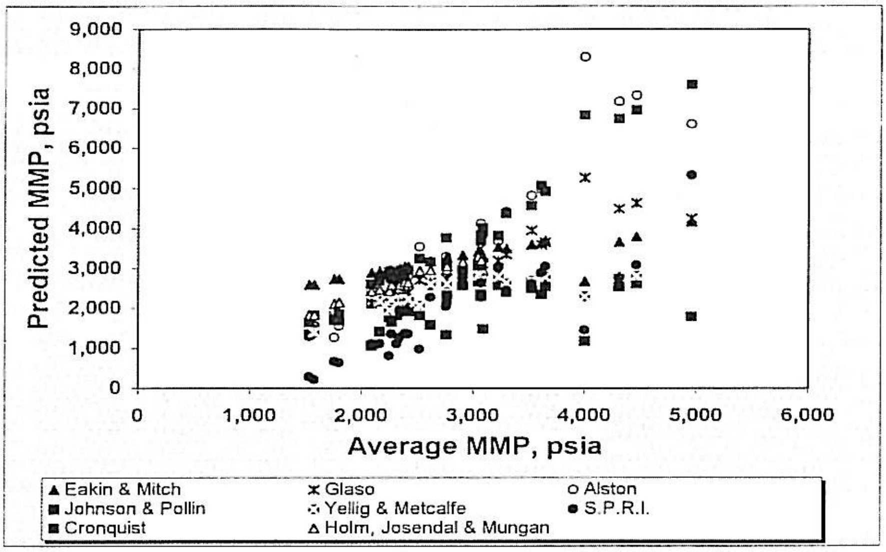

Fig. 1. Comparison of CO_2 MMP predictions by different correlations.

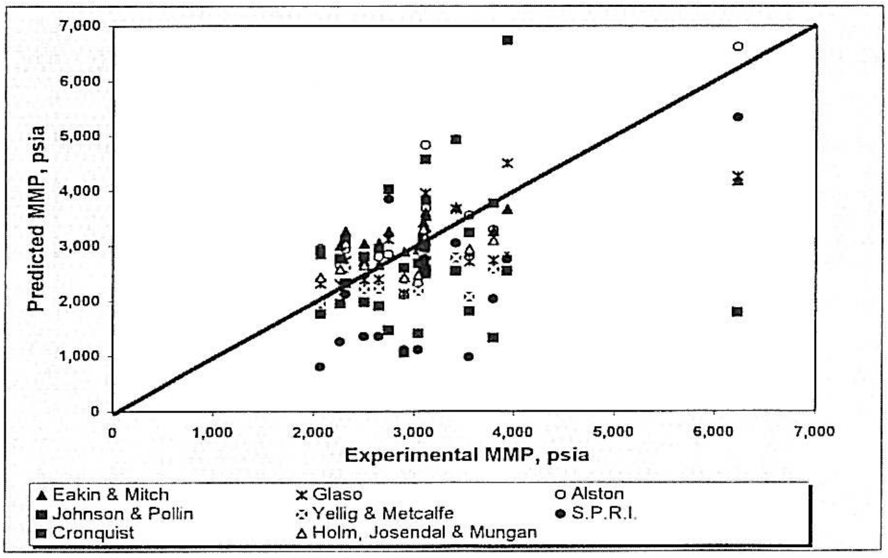

Fig. 2. Comparison between experimental and predicted CO_2 MMP.

Table 3. Predicted and measured CO_2 MMP.

Field	1 Holm, Josendal and Mungan 1974	2 Cronquist 1978	3 S.P.R.I 1979	4 Yellig and Metcalf 1980	5 Johnson and Pollin 1981	6 Alston 1985	7 Glaso 1985	8 Eakin and Mitch 1988	Exper. MMP psia	Current Pressure Psia	Initial Pressure
Sarir C-Main	O.O.R	4,562	2,600	2,690	2,494	4,823	3,948	3,593	3,112	2,919	3,924
Sarir c_North	3,150	2,964	2,756	2,800	2,562	2,782	2,879	3,327	3,104	2,645	3,921
Sarir L	3,300	3,114	3,080	2,820	2,667	2,956	3,021	3,415	3,089	3,141	4,021
Messla	O.O.R	3,817	3,014	2,780	2,573	3,669	3,190	3,531	3,118	2,869	3,985
N.A.U (TBG)	O.O.R	6,738	2,756	2,800	2,543	7,174	4,489	3,657	3,930	2,789	4,287
N.N.U (BAM)	O.O.R	6,956	3,080	2,820	2,622	7,332	4,644	3,793		2,944	4,710
Haram	O.O.R	6,841	1,448	2,300	1,179	8,293	5,270	2,675			2,027
Kotla	2,940	3,233	978	2,070	1,818	3,540	2,710	2,885	3,550	1,620	2,465
Nasser North	2,470	2,680	1,114	2,180	1,413	2,306	2,183	2,929	3,040	2,264	2,472
Nasser South	2,600	2,883	1,114	2,180	1,812	2,719	2,265	2,961		2,308	2,472
Nasser S.E	2,580	2,767	1,255	2,200	1,953	2,653	2,309	2,998	2,258	2,318	2,472
Raguba	2,950	3,157	2,268	2,600	1,583	2,563	2,647	3,177		1,853	2,400
Jebel	3,100	3,756	2,037	2,580	1,331	3,283	2,736	3,255	3,790	2,656	3,390
LDM	O.O.R	4,017	3,842	O.O.R	1,471	2,846	3,117	3,261	2,740	3,612	4,043
Bahi PL7	2,120	1,732	681	1,900	1,703	1,267	1,880	2,736		865	1,203
Dahra Jofra PL5	1,836	1,648	288	1,605	1,347	1,298	1,633	2,584		617	974
Samah	O.O.R	3,689	2,268	2,600	2,363	4,123	3,064	3,396		2,605	2,720
Waha North	2,650	2,800	1,352	2,220	1,977	2,643	2,388	3,040	2,500	2,310	2,978
Waha South	2,650	2,950	1,352	2,220	1,914	2,798	2,396	3,043	2,644	2,322	2,978
Defa	2,430	2,908	805	1,950	1,769	2,948	2,314	2,842	2,065	2,353	2,505
Gialo Eocene	1,840	1,825	220	1,400	1,465	1,574	1,707	2,580		726	1,191
Gialo Paleocene	3,050	3,095	2,123	2,600	2,321	2,942	2,731	3,257	2,315	2,384	2,741
Dahra PL7/YPL7	2,150	1,856	641	1,900	1,697	1,561	1,863	2,732		959	1,144
Amal B	O.O.R	4,371	2,447	2,620	2,388	4,422	3,349	3,494		2,650	4,690
Amal E	O.O.R	5,075	2,884	2,820	2,338	4,974	3,584	3,641		3,200	4,690
Amal N	O.O.R	4,924	3,047	2,780	2,544	4,932	3,654	3,691	3,414	3,050	4,690
Ghani L-Farrud	2,425	2,594	1,114	2,390	1,059	2,103	2,129	2,888	2,900	2,026	2,355
Zenad Farrud	2,580	2,737	1,352	2,220	1,648	2,401	2,250	2,959		1,920	2,400
Intisar – D	3,200	3,830	2,631	2,690	2,291	3,630	2,918	3,370		4,396	4,272
Abu - Attifel	O.O.R	7,595	5,323	O.O.R	1,784	6,613	4,251	4,165	6,224	6,049	6,883

- O.O.R. = Out of range

On the basis of the above discussion, it was concluded that the correlations of Holm, Josendal and Mungan, yellig-Metcalf, Glaso, and Eakin-Mitch are the best for screening purposes compared to others.

B. Miscible HC gas (Vaporising drive)

Firoozabadi and Aziz proposed a simple correlation to estimate MMP for vaporizing drive mechanism. Three parameters seem to affect multiple-contact misciblility of a reservoir fluid: the amount of intermediates in a reservoir fluid (C2 through C5, CO_2 and H_2S), the volatility of the reservoir oil which was represented by the C7+ molecular weight and the reservoir temperature.

Glaso proposed two correlations for N2 gas injection. The first one in 1985 and the other one modified in 1990. Both of Glaso's correlations are function of reservoir temperature, molecular weight of C7+ in stock-tank oil, and the intermediate contents (C2 through C6) in the reservoir oil. However, more additional data (API gravity and C1 content in the reservoir oil) are required for the modified one.

The predictions made with these correlations vary widely. Owing to the limited experimental data for the vaporizing drive, it was not possible to choose between these two correlations.

The correlations of Firoozabadi and Aziz were developed based on results with lean hydrocarbon gases. On the other hand, the correlations of Glaso were developed based on the results with Nitrogen. Hence, it was decided to make predictions using the correlations of Firoozabadi and Aziz. The results are summarized in Table 4.

C. Miscible HC gas (Condensing drive)

Glaso's correlations are given in the form of analytical expression. These give the MMP as a function of "Corrected molecular weight of C7+ in the stock-tank oil", the methane content in the injection gas and the reservoir temperature. These different equations are given corresponding to 34, 44 and 54 of the molecular weight of C2 through C6 in the injection gas. The equations were inverted to predict the MMC at the initial pressure of the reservoirs for gases with C2 through C6 molecular weight of 34, 44 and 54. These were then compared with the prediction made using Benham *et al.*'s correlation.

The results are given in Table 5. It is seen that the predictions made by both correlations are in good agreement with each other. Table 6 confirms this good agreement between the two correlations compared to the existing experimental data.

Based on the discussion above, it is concluded that the correlations of Glaso and Benham *et al.*, are equally good.

Table 4. Predicted lean gas MMP.

Field	1 Glaso 1985	2 Glaso 1990	3 Firoozabadi and Aziz 1986
Sarir C-Main	7,993	9,017	5,562
Sarir c_North	4,891	9,726	5,634
Sarir L	5,027	4,348	5,829
Messla	4,899	6,236	4,781
N.A.U (TBG)	10,937	8,405	6,980
N.N.U (BAM)	11,070	8,374	6,929
Haram	19,376	23,724	8,050
Kotla	6,420	8,687	5,956
Nasser North	4,315	4,906	4,404
Nasser South	4,473	5,840	4,433
Nasser S.E	4,742	6,416	5,021
Raguba	4,361	6,487	4,167
Jebel	4,942	5,193	5,167
LDM	5,134	4,212	4,455
Bahi PL7	4,260	3,123	3,533
Dahra Jofra PL5	4,292	8,871	3,820
Samah	6,630	13,405	6,973
Waha North	4,506	5,957	4,643
Waha South	4,523	5,716	4,881
Defa	5,062	6,441	5,365
Gialo Eocene	5,143	18,680	5,880
Gialo Paleocene	4,566	6,485	4,835
Dahra PL7/YPL7	4,675	8,850	4,549
Amal B	6,002	6,461	5,585
Amal E	6,544	6,226	5,678
Amal N	6,272	6,418	5,680
Ghani L-Farrud	4,273	4,518	3,989
Zenad Farrud	4,554	5,133	4,840
Intisar – D	5,282	6,005	5,878
Abu - Attiffel	7,199	4,953	6,416

EOR PROCESS RECOMMENDATIONS

The second part of this study is to recommend the suitable EOR process for each candidate reservoir. During the last few years,

Table 5. Prediction of HC MMC using different correlations.

Field	Initial Pressure	Temp.	Mwt C5+	Benham's Correlation Pred. MMC C1 Mole % C2-C4 Mwt of Injected Gas			Glaso's Correlation Pred. MMC C1 Mole % C2-C4 Mwt of Injected Gas		
	psia	Deg. F		34	44	58	34	44	54
Sarir C-Main	3,924	225	255	47.0	56.0	66.0	21.5	55.5	55.5
Sarir C_North	3,921	230	187	52.0	61.0	67.0	50.6	64.5	67.0
Sarir L	4,021	240	190	51.0	60.0	63.0	49.0	63.5	66.0
Messla	3,985	238	205	50.0	59.0	65.0	42.5	61.7	63.6
N.A.U (TBG)	4,284	230	279	34.0	52.0	64.0	15.0	54.8	53.6
N.N.U (BAM)	4,710	240	274	37.0	45.0	56.0	17.5	56.5	55.0
Haram	2,027	184	363	12.0	38.0	47.0	-	35.5	35.0
Kotla	2,465	164	249	44.0	57.0	63.0	23.5	53.0	55.4
Nasser North	2,472	170	187	51.0	60.0	66.0	42.5	59.5	63.0
Nasser South	2.472	170	211	50.0	60.0	65.0	39.0	58.0	61.5
Nasser S.E	2,472	176	202	47.0	55.0	63.0	39.0	57.6	61.0
Raguba	2,400	214	172	49.0	61.0	66.0	35.0	53.5	57.5
Jebel	3,390	206	196	56.0	67.0	69.0	43.0	61.5	64.0
LDM	4,043	262	156	62.0	65.0	74.0	53.0	63.3	66.7
Bahi PL7	1,203	150	167	39.0	44.0	57.0	-	35.0	40.0
Dahra Jofra PL5	974	129	164	28.0	44.0	47.0	-	-	-
Samah	2,720	214	232	44.0	50.0	63.0	27.0	52.0	55.5
Waha North	2,978	180	202	55.0	62.0	68.0	44.0	61.5	64.0
Waha South	2,978	180	203	55.0	62.0	68.0	44.0	61.5	64.0
Defa	2,505	156	228	50.0	56.0	66.0	34.0	57.6	60.4
Gialo Eocene	1,191	125	212	32.0	46.0	50.0	23.0	43.5	51.0
Gialo Paleocene	2,741	209	198	45.0	56.0	62.0	36.5	55.5	59.5
Dahra PL7/YPL7	1,144	148	179	23.0	40.0	49.0	3.0	30.0	40.0
Amal B	4,690	220	229	48.0	58.0	66.0	41.0	64.8	64.8
Amal E	4,690	234	231	44.0	56.0	65.0	37.8	62.8	63.0
Amal N	4,690	239	230	44.0	56.0	65.0	37.0	62.0	62.5
Ghani L-Farrud	2,355	170	177	45.0	58.0	64.0	42.5	59.5	62.5
Zenad Farrud	2,400	180	182	48.0	58.0	63.0	41.5	58.5	62.0
Intisar – D	4,272	226	195	56.0	66.0	67.0	51.0	66.0	67.8
Abu - Attifel	6,883	300	223	-	-	-	49.5	68.5	67.5

Table 6. Measured and predicted HC MMC.

Field	Pressure psia	Temp. Deg. F	Mwt C5+	Interm. Mwt of Inj. Gas		LPG Required%	C1 Conc. Inj. Gas (Mole%)		
				C2-C4	C2-C6		Exp	Benham	Glaso
Nasser North	2,300	170	187	44.2	44.6	17.8	51.6	57.6	57.8
Nasser S.E	2,312	170	202	45.7	46.3	20.0	53.6	56.3	56.7
Waha North	2,041	180	183	50.0	50.4	34.3	52.5	55.4	55.7
Waha South	2,314	180	188	50.0	50.4	34.3	52.3	58.4	59.3
Defa	2,200	156	213	48.1	48.9		59.9	58.9	58.1

the EOR department carried out a survey of the availability of gases for EOR processes. Both HC and CO_2 gas reserves were compiled.

A directive was given to OPCOs to give priority to CO_2 injection schemes. Our recommendation follows the same guidelines. First, we checked whether the initial reservoir pressure was greater than the pressure required to achieve miscibility with CO_2. If it is greater, than we conclude that it will be feasible to implement the miscible CO_2 flood for this reservoir and recommend detailed investigations of this scheme. Underlying this is the assumption that it will be possible to operate the reservoir at the initial reservoir pressure. This should be possible for most of the reservoirs, though one must be cautious.

Condensing gas drive requires blending of field gases with rich fluids like LPG or condensate, *etc.* These are expensive and not available in surplus quantities. Hence, we are of the opinion that, wherever feasible, the vaporizing gas process will perform better than the condensing gas process. On this basis, candidate reservoirs, where CO_2 flood is not feasible, are considered for vaporizing HC gas process.

The condensing miscible hydrocarbon flood and immiscible CO_2 injection schemes are evaluated for reservoirs where both the miscible CO_2 and vaporizing hydrocarbon floods are not feasible. It is not easy to evaluate the relative merits of the rich gas miscible floods vis-à-vis the immiscible CO_2 flood.

There is very little information available in the literature to carry out a good evaluation of immiscible CO_2 flood. Hence, we have ranked the immiscible CO_2 flood as the last choice. It must be emphasized that the relative ranking of the two schemes is not governed by process considerations, but rather by the data available to carry out the screening.

The results, given in Table 7, indicate the possibility of using miscible CO_2 for most of our candidates. Twenty out of 26 candidates could be subjected for miscible CO_2 flood. Abu Attiffel field is the only candidate where miscible CO_2 and lean gas injection schemes appear feasible. The lean gas injection is not feasible in any other candidate.

We have evaluated the feasibility of the other gas injection schemes, rich gas miscible flood and CO_2 immiscible flood, for the remaining six candidates. As discussed earlier, the condensing HC gas drive requires blending of field gases with rich fluids. To get a feel for the amount of rich gases required for achieving miscibility, predictions were made using "typical" composition of "field gas" and "LPG" as given in Table 8. The predictions were made for five of the remaining six candidates which are not suitable for miscible CO_2 flood. (The sixth candidate Gialo Eocene, had already been tested experimentally for immiscible CO_2 and condensing gas drive.) The results are given in Table 9. From this Table it appears that Kotla and Raguba fields are likely candidates for rich gas injection. The other three require significant amounts of LPG and hence are unlikely to be candidates for this process.

Table 8. Assumed composition of dry gas (DG) and LPG gas used for the prediction.

Component	DG %	LPG %
CO2	2.69	0.00
H2S	0.59	0.00
N2	1.39	0.00
C1	66.98	0.00
C2	14.24	2.63
C3	9.07	29.09
IC4	1.24	22.72
NC4	2.67	45.56
IC5	0.56	0.00
NC5	0.57	0.00

Table 7. EOR process recommendation.

Field	This Study				OPCO's EOR Program
	Misc. CO_2	Lean Gas	Rich Gas	IMM. CO_2	
Sarir C-Main	Yes				Miscible CO_2
Sarir c_North	Yes				Miscible CO_2
Sarir L	Yes				Miscible CO_2
Messla	Yes				Miscible CO_2
N.A.U (TBG)	Yes				Miscible CO_2
N.N.U (BAM)	Yes				Miscible CO_2
Kotla*			Yes		Miscible CO_2
Nasser North*	Yes				Miscible CO_2 & HC Gas
Nasser South	Yes				Miscible CO_2 & HC Gas
Nasser S.E	Yes				Miscible CO_2 & HC Gas
Raguba			Yes		Miscible CO_2 & HC Gas
Jebel*	Yes				Miscible CO_2 & HC Gas
Bahi PL7				Yes	Miscible HC Gas
Dahra Jofra PL5					Miscible HC Gas
Waha North	Yes				Miscible CO_2 & HC Gas
Waha South	Ys				Miscible CO_2 & HC Gas
Defa	Yes				Miscible CO_2
Gialo Eocene				Yes	Immscible CO_2 & HC Gas
Gialo Paleocene	Yes				Miscible CO_2 & HC Gas
Dahra PL7/YPL7				Yes	Immscible CO_2 & HC Gas
Amal B	Yes				Miscible CO_2
Amal E	Yes				Miscible CO_2
Amal N	Yes				Miscible CO_2
Ghani L-Farrud*	Yes				Miscible CO_2 & HC Gas
Zenad Farrud	Yes				Miscible CO_2 & HC Gas
Abu - Attifel	Yes	Yes			Miscible CO_2 & HC Gas

* Experimental CO_2 MMP is higher than the initial pressure

Table 9. Predicted LPG requirement using the above composition and Benham, *et. al.*, correlation.

Field	Pressure Psia	Temp. Deg. F	Mwt C5+	Benham Correlation @ Intermediate MWt of injected gas = 45	LPG Mole %
Kotla	2465 I 2065 C	164	249	C1 Mole % = 57.4 = 52.5	14.5 21.5
Raguba	2400 I 1865 C	214	172	= 61.2 = 52.0	9.0 22.0
Dahra- Jofra PL5	974 I 636 C	129	164	= 44.0 = 35.0	34.0 47.0
Bahi – PL7	1203 I 897 C	150	167	= 44.0 = 33.0	34.0 50.0
Dahra – PL7/YPL 7	1144 I 1020 C	148	179	= 40.0 = 36.0	40.0 46.0

I = Initial Pressure, C= Pressure as of Dec. 1990

The only choice for these three candidates is the possibility of applying immiscible CO_2 injection. However, we need some guidelines or criteria to decide whether this process can be successfully implemented in these reservoirs. Detailed experimental work carried out for the Gialo Eocene crude and the simulation carried out for the reservoir under CO_2 injection enabled us to get some initial guidelines. The results show that a high degree of enrichment is required for HC gas to achieve the miscibility limits (62.5 mole % of condensate Faregh gas). Compared to this, the reservoir fluid can dissolve a significant amount of CO_2 (730 scf/stb) at the initial pressure (1191 psia). The resulting CO_2-saturated oil viscosity is low (0.634 cp) compared to the initial oil viscosity of 2.25 cp. The resulting swelling factor is 1.35 rb/stb compared to the original FVF of 1.048 rb/stb. Accordingly, a very preliminary criterion for the applicability of immiscible CO_2 flood can be formulated as:

i) low initial solution GOR, and
ii) good solubility of CO_2 in the reservoir fluid.

Simon and Graue's correlations were used to predict the properties of the CO_2- swollen oils for Bahi PL-7, Dahra PL-7, YPL-7 complex and Dahra-Jofra PL-5 unit. The results are given in Table 10. The reservoir fluids of Bahi PL-7 and Dahra PL-7 YPL-7 complex are able to dissolve significant amounts of CO_2 in the reservoir fluid (516 and 439 scf/stb for both reservoirs respectively) and reduce the viscosity of the reservoir fluid.

The case of Dahra-Jofra PL-5 reservoir is different. The bubble point pressure is almost equal to the initial pressure and the viscosity of the original reservoir fluid is low. Therefore, immiscible CO_2 injection is not recommended in this case.

Based on the analysis carried out above, we conclude that Kotla and Raguba are potential candidates for miscible hydrocarbon flood using rich gases, and Bahi PL-7 and Dahra PL7 YPL-7 complex reservoirs are candidates for immiscible CO_2 flood. Dahra-Jofra unit appears to be unsuitable for any of the EOR schemes considered so far.

COMPARISON BETWEEN THE RECOMMENDED EOR PROCESSES AND THE PROGRAMMES OF OPERATING COMPANIES

The current EOR programmes of the operating companies were reviwed in the light of the results generated herein as described in Table 7. A good consistency between the OPCO's EOR programmes and the results of this study was noted, except in the cases of Kotla and Bahi PL-7 candidates.

For Kotla field the company has proposed to handle only miscible CO_2 tests for this field. Based on the prediction of correlations the miscibility will not be achieved at the initial reservoir conditions. Our analysis shows that for this reservoir, condensing gas miscible flood can be realized with enrichment of the field gas with small amounts of LPG.

For Bahi PL-7 field, the OPCO has proposed to conduct only the condensing gas drive tests. Based on the prediction of correlations, significant quantities

Table 10. Using Simon and Graue correlation for predicting solubility, swelling and viscosity of CO_2 – crude oil.

		Bahi PL-7	Dahra-PL7/PL7	Dahra Jofra PL5
Stock – tank oil gravity	Deg API	43.9	38.6	43.7
Oil density at 60° F	gm/cc	0.806	0.831	0.807
Avg. M.Wt of stock –tank oil		160	186	161
Watson k-factor		11.44	11.35	11.14
Initial pressure	psia	1203	1144	974
Temperature	Deg F	150	148	129
CO_2 solubility in STO (from Corr.)	Scf/Stb	716	588	599
Original solution GOR (from PVT)	Scf/Stb	200	149	427
CO_2 solubility in res. fluid	Scf/Stb	516	439	172
FVF of CO_2 saturated res. fluid	(From corr.)	1.27	1.22	1.27
FVF of original res. fluid	(From PVT)	1.109	1.086	1.232
Swelling factor		1.145	1.123	1.031
Initial oil viscosity	cP	1.104	1.254	0.6
Estimated CO_2 sat. oil viscosity	cP	0.4	0.55	

of LPG are required to achieve the miscibility (34% of LBG at the initial conditions and 50% of LPG at the current condition). At the same time, the immiscible CO_2 injection seems to be attractive, especially for this shallow reservoir. Based on Simon and Graue2 s correlation, the reservoir fluid of Bahi PL-7 has the ability to dissolve significant amounts of CO_2 gas (516 scf/stb).

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