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ADVANCED RESERVOIR CHARACTERIZATION AND EVALUATION OF CO_2 GRAVITY DRAINAGE IN THE NATURALLY FRACTURED SPRABERRY TREND AREA

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Objective

The overall goal of this project is to assess the economic feasibility of CO_2 flooding the naturally fractured Spraberry Trend Area in west Texas. This objective is being accomplished through research in four areas: 1) extensive characterization of the reservoirs, 2) experimental studies of crude oil/brine/rock (COBR) interaction in the reservoirs, 3) analytical and numerical simulation of Spraberry reservoirs, and 4) experimental investigations on CO_2 gravity drainage in Spraberry whole cores. Additionally, a 10-acre field demonstration pilot project is part of this project.

A Gravity Drainage Experiment in Long, Whole Diameter Core

The investigation of oil recovery by water imbibition followed by CO_2 gravity drainage, initiated during the third quarter of 1998 using Berea core is completed. The experiment was initially designed to use a Berea core and a Spraberry reservoir core. As the experiment on Spraberry core has not been completed at the time of this writing, only the results from the Berea core experiment are presented in this quarterly report. The experiment models the actual field experience of first waterflooding and then CO_2 recovery gravity drainage in a naturally fractured reservoir. The results from a four in diameter Berea core approximately 21.75 in long with permeability of about 610 md and 22.43% porosity demonstrate that CO_2 gravity drainage could significantly increase oil recovery after waterflooding in the naturally fractured Spraberry Trend Area. Water imbibition followed by CO_2 injection may be more efficient than injecting CO_2 alone. The efficiency of CO_2 injection decreases as permeability decreases and initial water saturation increases. Cyclic CO_2 injection could enhance oil recovery during a CO_2 gravity drainage process. Temperature does not have a significant effect on the oil recovery during CO_2 gravity drainage process.

Introduction

During the first three years of this project, five experiments were performed on two 4-in. Berea cores, one 4-in. reservoir core, one 3.5-in. reservoir core and two 2.5-in. reservoir cores. The cores were taken from the Spraberry reservoir. The permeabilities to brine of 4-in. and 3.5-in. Spraberry cores, are 0.01 md and 0.38 md, respectively. The absolute permeabilities of the two 4 in Berea cores are 500 md and 50 md, respectively. The two 2.5-in. reservoir cores, which were stacked vertically during the experiment, have air permeabilities of 0.16 md and 0.13 md, respectively, while an average permeability to brine of 0.057 md was measured for the whole stack during the experiment. Table 1 summarizes the physical properties of those whole cores.

All five experiments were conducted to investigate the efficiency of CO_2 gravity drainage and the effect of initial water saturation during CO_2 gravity drainage experiments. The last experiment, which used a stack of two 2.5-in. Spraberry cores, was also performed to investigate the effects of core discontinuity and impermeable layers at the top and the

bottom of the pay zone on the efficiency of the CO_2 gravity drainage. The partial results are also presented in Table 1.

Figure 1 summarizes the results (oil recovery curves) of all five experiments, which were given in the Third Annual Technical Progress Report. The results are redrawn in Figs. 2 and 3 as curves of oil recovery vs. rock permeability and oil recovery vs. initial water saturation. It is clearly seen from the figures that the efficiency of CO_2 injection decreases as permeability decreases and initial water saturation increases. It appears that core discontinuity and impermeable layers at the top and bottom of the pay zone affect the efficiency of the CO_2 gravity drainage, as can be seen by comparing the result of the last experiment (stacked core, K= 0.05 md and Sw_I = 0.376) with that of the third experiment (continuous core, K= 0.01 md and Sw_I = 0.386). The permeability and the water saturation of the cores are almost similar for that experiment but the recovery from stacked core (19% IOIP) is lower than the continuous core (31% IOIP) as shown in Table 1. Figures 2 and 3 show that the effect of initial water saturation on oil recovery is more pronounced than the effect of permeability.

In order to optimize the CO_2 pilot design in the E.T. O'Daniel Unit of the Spraberry Trend Area, the previous experimental results were scaled up to field scale using the mathematical model proposed by Schechter and Guo (1996). The modeling results indicate that significant amounts of oil can be recovered from the pilot area by CO_2 flooding in a relatively short time period, depending on matrix permeability, initial water saturation and fracture intensity.

During the fourth year of this project, another experiment was performed to model the actual field experience of first flooding and then CO_2 recovery in the naturally fractured Spraberry Trend Area. The objective of the experiment is to investigate the effect of water imbibition followed by CO_2 gravity drainage on oil recovery under reservoir conditions. The effects of temperature and cyclic CO_2 injection were also investigated during the experiment. The experiment was initially designed to use a Berea core and a reservoir core from the Spraberry Trend Area. As the experiment on the Spraberry core has not been completed at the time of this writing, only the results from the experiment of the Berea core are presented in this report.

Laboratory Experiment

Materials used in the experiment

Core Sample. A 4-in. Berea core 21.75 in. long was used in this experiment. The total bulk volume is 4476.62 cm^3 and the pore volume is 1004.0 cm^3. Thus the calculated porosity is 22.43%. The permeability of the Berea core was measured under room temperature (26°C) using synthetic Spraberry brine. Permeabilities to brine measured were 625.97, 619.78, 609.45, 600.50 and 593.68 md, corresponding to the pressure drops of 3.2, 5.5, 7.4, 9.5 and 13.2 psia. Therefore, the average permeability of the core to brine is 610 md. The physical properties are given in Table 2.

Brine. Synthetic Spraberry brine was used in the experiment. Density and viscosity of the brine is 1.08 g/cm^3 and 1.21 cp, respectively, measured under room temperature (26°C) and ambient pressure (12.6 psia).

Oil. Spraberry dead oil was used in the experiment. The composition of the oil was obtained from GC analysis as shown in Table 3. The average molecular weight of the dead oil is 230.4, oil density is 0.865 g/cm^3 and oil viscosity is 2.956 cp measured under room conditions.

Core preparation

Cleaning. The core was put into a core holder and cleaned under room temperature by injecting methanol, toluene, THF and chloroform. Methanol was at first injected in order to remove potential salts in the core. Then the four solvents were alternatively injected. Finally, methanol was injected once again to remove all other solvents. The core was first flushed with N_2 to remove methanol inside the core and then with moist N_2 in order to recover its wettability. The core was then vacuum-pumped. After being cleaned, it was taken from the core holder and put into another oven under high temperature for drying.

Saturation. The core was put back into the core holder and air was removed from inside the core using a vacuum pump. Synthetic Spraberry brine was injected from the bottom of the core. A total of 1004 cm^3 brine was put into the core, so the porosity, ϕ, can be estimated at about 22.43 %. The synthetic brine then was flushed through the core. The permeability of the core was measured under room temperature (26°C) after the flow was stable.

Spraberry dead oil was injected into the core from the top under reservoir temperature of 58.9^{o}C (138°F). The oil flow rate was 0.0225 cm^3/s (81 cm^3/hr) at the pressure difference of 2.2 psi, and later increased to 0.0451 cm^3/s (162 cm^3/hr) at the pressure drop of 5.1 psi. Oil broke through when 525 cm^3 of brine was produced. The total amount of dead oil injected was 1169 cm^3 (1.16 PV). The water saturation, S_w, and the oil saturation, S_o, were 42.6% and 57.4%, respectively. After aging core for 10 days under reservoir temperature 58.9^o C (138° F) with pressure above 1600 psia, the core was flushed by injecting1350 cm^3 (1.35 PV) dead oil. Another 5.3 cm^3 brine was produced. Therefore, the total volume of oil within the core increased to 581.3 cm^3 and the initial oil saturation, S_{oi}, was 57.9 %. The initial water saturation, S_{wi}, decreased to 42.1%.

Procedure and experimental results

Figure 4 schematically illustrates the set-up used in this experiment. Basically, it consists of a drainage cylinder, a visual cell, a BPR, a pump, two accumulators for storing CO_2 and brine, an oil-gas separator and some glassware for measuring oil, gas and brine

produced. Reservoir temperature is 58.9^{o}C (138°F). The experiment was conducted in a drainage cylinder.

Water imbibition. The injection rate was 20 cm^3/hr and the backpressure was set above 1650 psia. A total of 194.38 cm^3 oil was produced during the water imbibition, which decreased the oil saturation from the initial oil saturation, 57.9% to 38.5%. The oil recovery was 33.44 % OOIP. The water saturation increased to 61.5%.

During water imbibition, a total of 138.9 cm^3 gas was produced at 12.6 psia. The gas volume was about 1.389 cm^3 under 1600 psia and temperature of 58.9^{o}C (138°F). If we assume a gas factor equal to 0.85, the gas volume is only 0.13% the pore volume. Therefore, the gas saturation effect can be ignored.

CO_2 gravity drainage/injection. CO_2 gravity drainage was performed in two stages: dynamic gravity drainage (open system) and static gravity drainage (closed system). For both stages, the backpressure was set above 1700 psia and the temperature was set at 58.9^{o}C (138°F). The total time for conducting CO_2 imbibition was 858 hours.

In the first stage, CO_2 was pumped into the drainage cylinder from the top and the injection rate was set up between 20 ~ 30 cm^3/hr. About 50 cm^3 black oil was produced approximately 40 hours after CO_2 injection initiated. Light oil was produced but the oil rate decreased significantly. This stage ran for about 330 hours after injecting about 7105 cm^3 (7.08 PV) CO_2.

In the second stage, the outlet was closed and CO_2 injection was stopped. The core, the CO_2 and the visual cell formed a closed system. The visual cell was connected to the bottom of the drainage cell to collect oil and water produced from the core. This stage ran for 528 hours. Not much CO_2 was used in this stage because CO_2 remained in the cell (closed system).

Thirteen oil samples were taken from the oil produced during CO_2 gravity drainage for a GC analysis. The colors of the oil samples changed from black to yellow and back to black.

A total of 93.2 cm^3 oil and 228.3 cm^3 water were produced during CO_2 gravity drainage. The oil recovery increased 16.03% OOIP, which made the total oil recovery increase to 49.4% OOIP. The oil saturation within the core decreased to 29.3% and the water saturation dropped to 39.0%. Assuming that only water and oil existed in the core before CO_2 drainage began, CO_2 saturation within the core was 31.7 %.

Temperature effect. To investigate the effect of temperature on CO_2 drainage, temperature was increased gradually to 180°F in two days. The pressure in the drainage cell increased to above 2300 psia. This process lasted 167 hours. Only 0.5 cm^3 of oil and 1.0 cm^3 of water were produced.

Cyclic CO_2 injection. The last step was cyclic CO_2 injection, where the CO_2 was injected at elevated pressure, and after a certain period of time, the injection was stopped, with CO_2 being released to a lower pressure. During the pressure decrease stage, CO_2 injection was stopped and CO_2 was slowly released from the drainage cylinder until the pressure went down to 1450 psia. Then, the outlet was closed and CO_2 was injected into the cylinder with the pressure kept above 1750 psi. Then the pressure decrease stage was run again. One cycle took about 24 hours. Oil and water were collected during the pressure decrease stage. A total of five cycles were run.

The volume of oil produced in this process was 13.1 cm^3, which increased oil recovery from 49.5 to 51.8% OOIP. The residual oil saturation dropped from 29.2 to 28.0%. The volume of water produced was 23.5 cm^3, which decreased water saturation to 36.5%.

Table 4 summarizes the experimental results. The oil and water producing histories are also plotted in Fig. 5. Figures 6 and 7 present the oil recovery and oil/water saturations vs. time, while Fig. 8 shows oil recovery and amount of CO_2 used during CO_2 injection/gravity drainage.

Analysis and Discussion

Our objective is to investigate effects of CO_2 gravity drainage after water imbibition on oil recovery under reservoir conditions. Thus, the discussion and analysis are concentrated on results obtained from CO_2 gravity drainage.

Nine of the 13 oil samples were analyzed using gas chromatography (GC). These oil samples were taken at different times. Table 5 shows the mole fraction and weight percent of different component groups in the oil samples. For convenient analysis, we divided the components of the oil samples into four groups: C1 ~ C10, C11 ~ C20, C21 ~ C30 and $C31^+$. The results are shown in Figs. 11 and 12. For more details, see Tables 7 and 8. The results are also presented in Figs. 9 and 10.

The CO_2 extracted most of middle components, C11 ~ C20, from the oil during CO_2 gravity drainage. The oil samples from this component group were about 85% by mole fraction and about 80 % by weight percent (Figs. 11 and 12). While more mole fraction of light components were extracted at the beginning of the experiment, the mole fraction of heavy components increased at the end of CO_2 injection/gravity drainage.

Oil sample densities were also measured at room temperature and ambient pressure. The average molecular weights of the samples obtained from GC analysis are presented in Table 6 and plotted in Fig. 13. The oil sample at time 0 was Spraberry dead oil. Both density and average molecular weight increased with time except at the beginning of the experiment. At that point, heavier components were flooded by CO_2 and then CO_2 extracted the light component about 40 hours later, which indicated that CO_2 drainage initiated.

Temperature seemed to have no significant effect on CO_2 drainage process in this experiment (Fig. 5), because CO_2 may have a more pronounced effect than temperature on increasing the mobility of oil and decreasing the interfacial tension (IFT).

Cyclic CO_2 injection may prove effective in improving the oil recovery during CO_2 gravity drainage, as displayed in Fig. 5. A cyclic injection scheme in this experiment enhanced the oil recovery up to 2.3% OOIP. Considering that cyclic CO_2 injection was performed at low oil saturation (29.2%), the oil increment may be considered significant.

Figure 8 shows the volume of CO_2 used during CO_2 injection/drainage. A large quantity of CO_2 was used in this experiment. It should be noted also that the rate of pumping CO_2 into the drainage cell did not significantly affect the final oil recovery from the core, but only increased the amount of CO_2 usage as shown in Fig. 8. The oil production rate did not decrease when CO_2 injection was stopped. The only significant effect of the CO_2 injection rate may be on the oil production rate at the beginning of the CO_2 process. However, CO_2 injectivity studies need to be performed to clarify this issue.

Figure 14 shows that water imbibition followed by CO_2 injection may achieve higher oil recovery than using CO_2 injection alone. That comparison was made between Core No. 1 (k = 500 md) and this experiment (k = 500 md) (see Table 1) because of almost similar rock properties.

Conclusions

From the results obtained in this experiment, the following conclusions can be drawn:

1. CO_2 gravity drainage could significantly increase oil recovery after waterflooding in the naturally fractured Spraberry Trend Area.
2. Water imbibition followed by CO_2 injection may be more efficient than injecting CO_2 alone.
3. The efficiency of CO_2 injection decreases as permeability decreases and initial water saturation increases.
4. The effect of initial water saturation may have more effect on oil recovery than permeability.
5. Cyclic CO_2 injection may enhance oil recovery during a CO_2 gravity drainage process.
6. Temperature does not have a significant effect on oil recovery during the CO_2 gravity drainage process.

References

1. Schechter, D.S.: "Advanced Reservoir Characterization and Evaluation of CO_2 Gravity Drainage in the Naturally Fractured Spraberry Trend Area," Third Annual Technical Progress Report, Contract No. DE-FC22-95BC14942, U.S. DOE, (Dec. 1998).
2. Schechter, D.S. and Guo, B.: "Mathematical Modeling of Gravity Drainage after Gas Injection into Fractured Reservoirs," paper SPE 35170 presented at the 1996 SPE Improved Oil Recovery Symposium Tulsa, April 22-24.

Table 1—Physical Properties of the Core Samples Used in Previous Experiments and Partial Results Obtained

Core No.	1	2	3	4	5
Core Type	Berea	Berea	Spraberry	Spraberry	Spraberry
Configuration	continuous	continuous	continuous	continuous	stacked
Length, cm	55.52	55.25	55.0	55.245	24.77 25.08
Diameter, cm	10.16	10.16	10.16	8.89	6.53 6.58
Porosity, %	18.7	13.0	10.0	11.1	10.7
Brine Permeability, md	500	50	0.01	0.38	0.057
Water Saturation, %	35.0	29.3	38.6	45.0	37.6
Residual Oil Saturation, %	37.5	32.5	42.5	41.8	50.5
OOIP, cc	544.5	411.1	273.8	209.3	111.0
OWIP, cc	293.2	171.2	172.1	171.3	67.0
Oil Recovery, %	42.0	54.0	30.8	24.0	19.1
Time of Experiment, (day)	6	220	190	167	331

Table 2—Physical Properties of the Core Sample Used in This Experiment

Properties of the Berea Core	**Value**
Length, cm	55.25
Diameter, cm	10.16
Bulk Volume, cm^3	4476.62
Pore Volume, cm^3	1004.0
Porosity, %	22.43
Brine Permeability, md	610.0
OOIP, %	581.3
OWIP, %	422.7
Initial Water Saturation, %	42.1
Initial Oil Saturation, %	57.9

Table 3—GC Results of the Spraberry Dead Oil Used in the Experiment

Carbon No.	Molec. wt.	Weight %	Moles	Mole fract.	Molec. wt. %
1	16.04303	0	0	0	0
2	30.07012	0	0	0	0
3	44.09721	0	0	0	0
4	58.12430	0	0	0	0
5	72.15139	0.084064563	0.001165114	0.002683957	0.193651205
6	86.17848	0.761713828	0.008838794	0.020361054	1.754684680
7	100.20557	4.299808405	0.042909874	0.098847226	9.905042626
8	114.23266	5.136605594	0.044966173	0.103584119	11.832689410
9	128.25975	4.251297195	0.033145996	0.076355148	9.793292159
10	142.28684	5.343655162	0.037555512	0.086512913	12.309648980
11	156.31393	3.725624838	0.023834247	0.054904594	8.582352830
12	170.34102	3.498245901	0.020536720	0.047308408	8.058562498
13	184.36811	3.682212712	0.019972070	0.046007678	8.482348616
14	198.39520	3.928306014	0.019800409	0.045612239	9.049249375
15	212.42229	3.053448865	0.014374428	0.033112945	7.033927635
16	226.44938	2.829626878	0.012495627	0.028784937	6.518331098
17	240.47647	3.067010969	0.012753892	0.029379878	7.065169311
18	254.50356	2.735307623	0.010747620	0.024758228	6.301057176
19	268.53065	1.868650564	0.006958798	0.016030294	4.304625171
20	282.55774	2.671345541	0.009454158	0.021778607	6.153714065
21	296.58483	2.231717507	0.007524719	0.01733395	5.140986518
22	310.61192	2.097276207	0.006752079	0.015554095	4.831287414
23	324.63901	1.886004976	0.005809545	0.013382874	4.344602811
24	338.66610	1.820107843	0.005374343	0.012380342	4.192802113
25	352.69319	4.814449489	0.013650531	0.031445377	11.09057030
26	366.72028	1.758789839	0.004795998	0.011048066	4.051549904
27	380.74737	1.765568922	0.004637114	0.010682060	4.067166205
28	394.77446	1.273149915	0.003225006	0.007429126	2.932829323
29	408.80155	1.844834162	0.004512787	0.010395659	4.249761686
30	422.82864	1.735618455	0.004104780	0.009455775	3.998172280
31	436.85573	3.053084504	0.006988771	0.016099339	7.033088293
32	450.88282	1.873150914	0.004154407	0.009570097	4.314992181
33	464.90991	2.543647873	0.005471270	0.012603624	5.859549596
34	478.93700	1.597259782	0.003335010	0.007682533	3.679449114
35	492.96409	1.604971432	0.003255757	0.007499966	3.697213677
36	506.99118	2.651509536	0.005229893	0.012047586	6.108019825
C37+	563.09954	14.51193399	0.025771525	0.059367309	33.429704590
Total/Average		100	0.434102968	1	230.3600927

Table 4—Experimental Results during Different Stages

	Water Imbibition	CO_2 Drainage	Temperature Increase	Cyclic CO_2 Injection
Initial Oil Saturation, %	57.9	33.5	29.3	29.2
Final Oil Saturation, %	33.5	29.3	29.2	28.0
Initial Water Saturation, %	42.1	66.5	39.0	38.9
Final Water Saturation, %	66.5	39.0	38.9	36.5
Gas/CO_2 Saturation, %	0.1	31.7	31.7	35.5
Oil Recovery, %	33.44	49.4	49.5	51.8
Time of Experiment, day	22	36	7	5

Table 5—GC Results of Different Group Components of Oil Samples Obtained from CO_2 Gravity Drainage/Injection

Time	***C1 ~ C10***		***C11 ~ C20***		***C20 ~ C30***		***C31+***	
(hr)	Mole frac.	Weight %	Mole frac.	Weight %	Mole frac.	Weight %	Mole frac.	Weight %
0	0.388344	19.87714	0.347678	31.05978	0.139107	21.22752	0.124870	27.83556
10	0.266333	16.76627	0.600432	58.15009	0.094344	15.58787	0.038891	9.495767
37	0.438436	29.86307	0.475120	51.93866	0.060512	11.19651	0.025932	7.001758
42.5	0.055843	3.423766	0.854845	83.13537	0.088145	13.17068	0.001167	0.270184
50.5	0.049993	3.011592	0.847875	81.78595	0.099050	14.51070	0.003082	0.691760
89	0.072391	4.696062	0.857835	84.41236	0.068740	10.64875	0.001034	0.242836
209.5	0.085529	5.485306	0.801255	77.32346	0.111675	16.83614	0.001541	0.355099
301	0.012867	0.709839	0.875925	83.48775	0.109502	15.46458	0.001705	0.337837
330	0.017890	1.042006	0.836478	75.82748	0.109121	15.46735	0.036511	7.663163
359.5	0.106067	4.144405	0.346742	23.13898	0.280836	30.83610	0.266355	41.88052

Table 6—Properties of Oil Samples Obtained from CO_2 Gravity Drainage/Injection

Time, hr	0	10	37	42.5	50.5	89	209.5	301	330	359.5
Ave. Molec. Weight	230.4	206.3	181.0	217.6	221.7	208.5	210.5	233.6	235.4	322.4
Density	0.865	0.864	0.852	0.823	0.844	0.833	0.832	0.848	0.870	0.901

Table 7—Mole Fraction of Oil Samples Obtained from CO_2 Gravity Drainage/Injection

Sample Carbon#	Dead oil	Sample #1	sample #2	sample #3	sample #4	Sample #5	sample #6	sample #7	sample #8	sample #9
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0.00268	0.00035	0.00042	0.00020	0.00008	0.00008	0.00006	0.00014	0.00048	0.00015
6	0.02036	0.00182	0.00871	0.00024	0.00017	0.00026	0.00023	0.00009	0.00002	0.00135
7	0.09885	0.01982	0.07283	0.00288	0.00237	0.00042	0.00302	0.00114	0.00009	0.01425
8	0.10358	0.04912	0.11511	0.00694	0.00620	0.00875	0.00853	0.0025	0.00080	0.02440
9	0.07636	0.06911	0.10832	0.01098	0.01049	0.01598	0.01714	0.00279	0.00226	0.02563
10	0.08651	0.12612	0.13305	0.03460	0.03069	0.04690	0.05654	0.00619	0.01424	0.04030
11	0.05491	0.09859	0.08972	0.05517	0.04488	0.07254	0.07913	0.01046	0.03824	0.03361
12	0.04731	0.09426	0.07957	0.09314	0.07964	0.10944	0.11267	0.02908	0.07255	0.03436
13	0.04601	0.09301	0.07277	0.11257	0.12060	0.14581	0.14459	0.07278	0.11012	0.04649
14	0.04561	0.09138	0.06381	0.11886	0.11265	0.16095	0.14222	0.16015	0.15203	0.03780
15	0.03311	0.05536	0.04199	0.15125	0.14637	0.10333	0.08909	0.14729	0.13196	0.03719
16	0.02879	0.04670	0.03544	0.09859	0.09721	0.08595	0.07213	0.14002	0.09595	0.03495
17	0.02938	0.04856	0.03695	0.08987	0.09316	0.07572	0.06834	0.13411	0.10036	0.03868
18	0.02476	0.03627	0.02705	0.05721	0.07329	0.04658	0.04525	0.09675	0.06479	0.03498
19	0.01603	0.02027	0.01581	0.04884	0.04328	0.03596	0.02917	0.05222	0.04226	0.02473
20	0.02178	0.01603	0.01201	0.02936	0.03680	0.02158	0.01867	0.03308	0.02823	0.02396
21	0.01733	0.01684	0.01564	0.02717	0.02752	0.02196	0.01971	0.02465	0.02986	0.03582
22	0.01555	0.01280	0.00847	0.01612	0.02323	0.01466	0.06393	0.02396	0.01816	0.03686
23	0.01338	0.00731	0.00620	0.01025	0.01238	0.00849	0.00727	0.01041	0.01285	0.02739
24	0.01238	0.00494	0.00353	0.00681	0.00827	0.00595	0.00488	0.00688	0.00958	0.02740
25	0.03145	0.03647	0.01744	0.02204	0.01975	0.01271	0.01165	0.03466	0.01572	0.03173
26	0.01105	0.00376	0.00238	0.00283	0.00354	0.00241	0.00195	0.00351	0.00593	0.02604
27	0.01068	0.00382	0.00154	0.00165	0.00218	0.00135	0.00117	0.00205	0.00519	0.02562
28	0.00743	0.00237	0.00149	0.00068	0.00095	0.00055	0.00046	0.00113	0.00329	0.01875
29	0.01040	0.00302	0.00191	0.00045	0.00089	0.00066	0.00056	0.00216	0.0077	0.02707
30	0.00946	0.00302	0.00192	0.00014	0.00035	0.00000	0.00010	0.00009	0.00086	0.02416
31	0.01610	0.00177	0.0039	0.00022	0.00026	0.00012	0.00030	0.00052	0.00613	0.04041
32	0.00957	0.00160	0.00335	0.00003	0.00008	0.00006	0.00009	0.00029	0.00192	0.02395
33	0.01260	0.00149	0.00179	0.00009	0.00005	0.00003	0.00005	0.00030	0.00558	0.01168
34	0.00768	0.00423	0.00270	0.00002	0.00064	0.00004	0.00006	0.00020	0.00386	0.04292
35	0.0075	0.01136	0.00622	0.00006	0.00047	0.00039	0.00054	0.00031	0.00422	0.02009
36	0.01205	0.01087	0.00396	0.00041	0.00122	0.00034	0.00046	0.00008	0.00642	0.01773
C37+	0.05937	0.00759	0.00401	0.00034	0.00037	0.00004	0.00006	0.00001	0.00837	0.10957

Table 8—Weight Percent of Oil Samples Obtained from CO_2 Gravity Drainage/Injection

Sample Carbon#	Dead oil	sample #1	sample #2	sample #3	sample #4	sample #5	sample #6	sample #7	sample #8	sample #9
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0.08407	0.01216	0.01675	0.00673	0.00247	0.00287	0.00222	0.00444	0.01473	0.00327
6	0.76171	0.07585	0.41457	0.00937	0.00654	0.01073	0.00944	0.00345	0.00057	0.03595
7	4.29981	0.96277	4.03216	0.13275	0.10711	0.02030	0.14357	0.04907	0.00384	0.44291
8	5.13661	2.71991	7.26451	0.36444	0.31964	0.47932	0.46298	0.12226	0.03883	0.86451
9	4.25130	4.29653	7.67572	0.64724	0.60674	0.98283	1.04470	0.15344	0.12309	1.01941
10	5.34366	8.69903	10.4594	2.26324	1.96909	3.20002	3.82240	0.37719	0.86095	1.77836
11	3.72563	7.47039	7.74821	3.96434	3.16355	5.43733	5.87671	0.69977	2.53889	1.62927
12	3.49825	7.78327	7.48817	7.29323	6.11800	8.93982	9.11862	2.12040	5.24956	1.81537
13	3.68221	8.31264	7.41246	9.54002	10.0280	12.8916	12.6647	5.74429	8.62417	2.65816
14	3.92831	8.78818	6.99383	10.8393	10.0795	15.3126	13.4050	13.6026	12.8124	2.32592
15	3.05345	5.70065	4.92830	14.7685	14.0220	10.5257	8.99132	13.3942	11.9075	2.45002
16	2.82963	5.12607	4.43446	10.2621	9.92809	9.33387	7.75970	13.5738	9.22973	2.45478
17	3.06701	5.66027	4.90898	9.93368	10.1037	8.73180	7.80800	13.8070	10.2522	2.88520
18	2.73531	4.47492	3.80324	6.69294	8.4122	5.68459	5.47126	10.5409	7.00441	2.76140
19	1.86865	2.63826	2.34560	6.02793	5.24131	4.63128	3.72143	6.00357	4.82074	2.05921
20	2.67135	2.19545	1.87542	3.81336	4.68968	2.92379	2.50668	4.00121	3.38793	2.09967
21	2.23172	2.42092	2.56221	3.70379	3.68095	3.12359	2.77740	3.13000	3.76143	3.29470
22	2.09728	1.92768	1.45368	2.30184	3.25395	2.18332	9.43365	3.18612	2.39594	3.55070
23	1.88601	1.15016	1.11231	1.52891	1.81258	1.32244	1.12068	1.44671	1.77158	2.75749
24	1.82011	0.81124	0.66065	1.06033	1.26245	0.96598	0.78458	0.99729	1.37755	2.87761
25	4.81445	6.23558	3.39843	3.57371	3.14109	2.14898	1.95245	5.23260	2.35507	3.47088
26	1.75879	0.66769	0.48276	0.47751	0.58559	0.42432	0.33983	0.55094	0.92360	2.96196
27	1.76557	0.70482	0.32340	0.28952	0.37409	0.24591	0.21212	0.33435	0.83997	3.02536
28	1.27315	0.45331	0.32402	0.12309	0.16967	0.10420	0.08706	0.19171	0.55115	2.29597
29	1.84483	0.59749	0.43134	0.08423	0.16386	0.12918	0.10844	0.37818	1.33719	3.43259
30	1.73562	0.61899	0.44773	0.02775	0.06647	0.00084	0.01994	0.01670	0.15388	3.16885
31	3.05309	0.37378	0.94125	0.04500	0.05143	0.02524	0.06187	0.09774	1.13757	5.47525
32	1.87315	0.34855	0.83466	0.00647	0.01627	0.01376	0.01854	0.05651	0.36835	3.34928
33	2.54365	0.33505	0.45840	0.01954	0.01053	0.00768	0.01035	0.06003	1.10272	1.68472
34	1.59726	0.98137	0.71374	0.00340	0.13761	0.00978	0.01318	0.04057	0.78533	6.37557
35	1.60497	2.71556	1.69478	0.01277	0.10382	0.09320	0.12560	0.06440	0.88457	3.07171
36	2.65151	2.67109	1.11019	0.09621	0.27864	0.08236	0.11099	0.01735	1.38304	2.78763
C37+	14.5119	2.07037	1.24874	0.08680	0.09347	0.01083	0.01460	0.00124	2.00158	19.1364

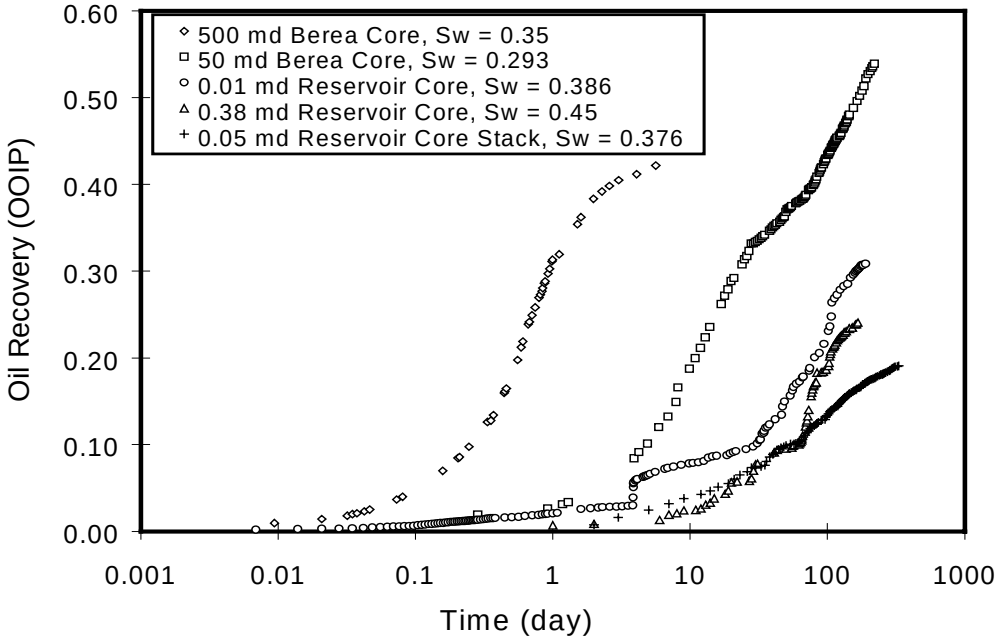

Fig. 1—Oil recovery curves obtained from the five experiments with different permeabilities and initial water saturations.

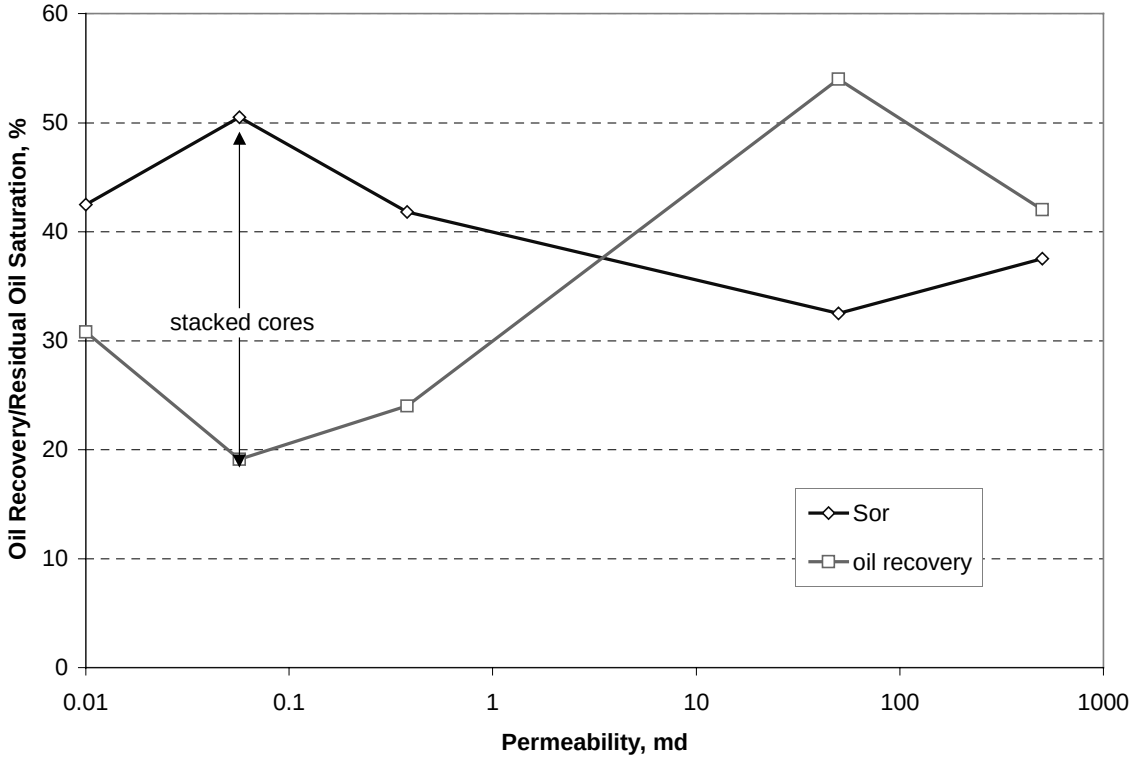

Fig. 2—Effect of permeability on oil recovery of CO_2 injection.

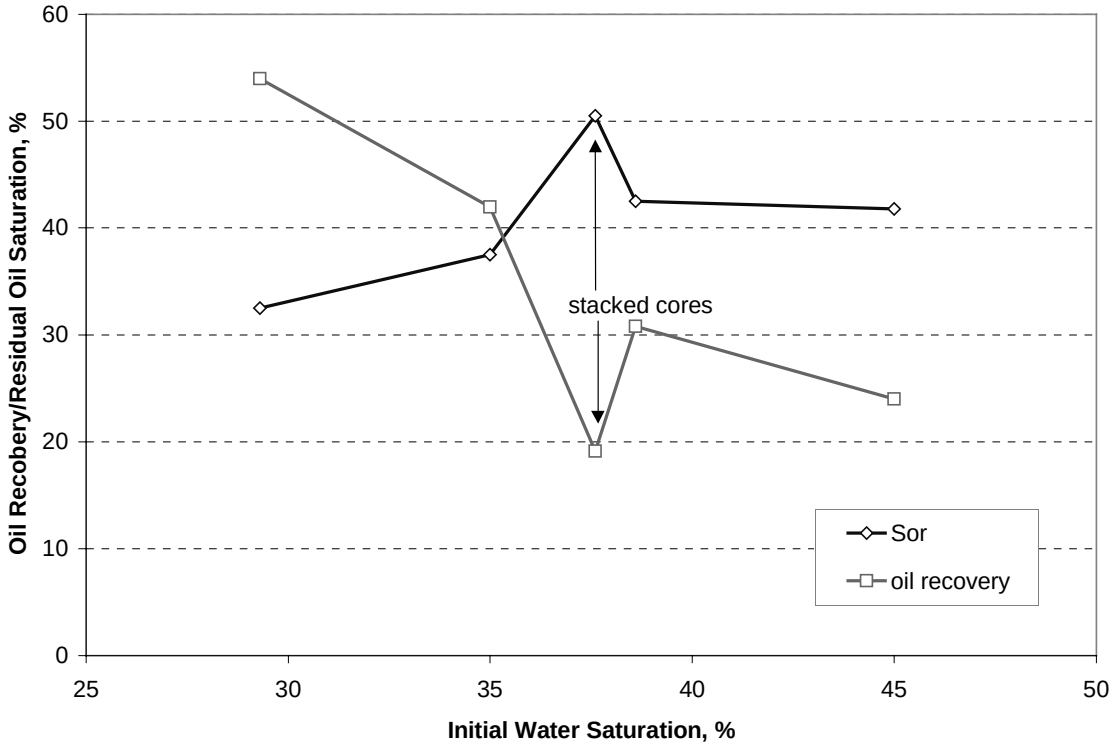

Fig. 3—Effect of initial water saturation on oil recovery of CO_2 injection.

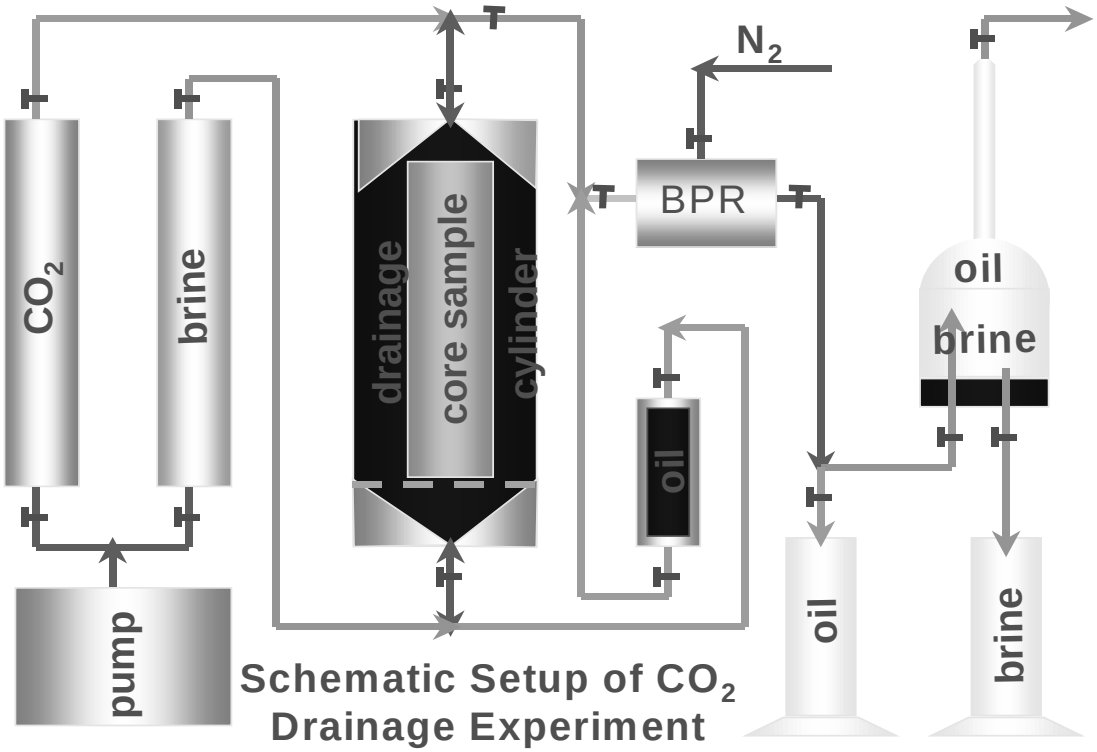

Fig. 4—Set up for water and CO_2 gravity drainage experiment.

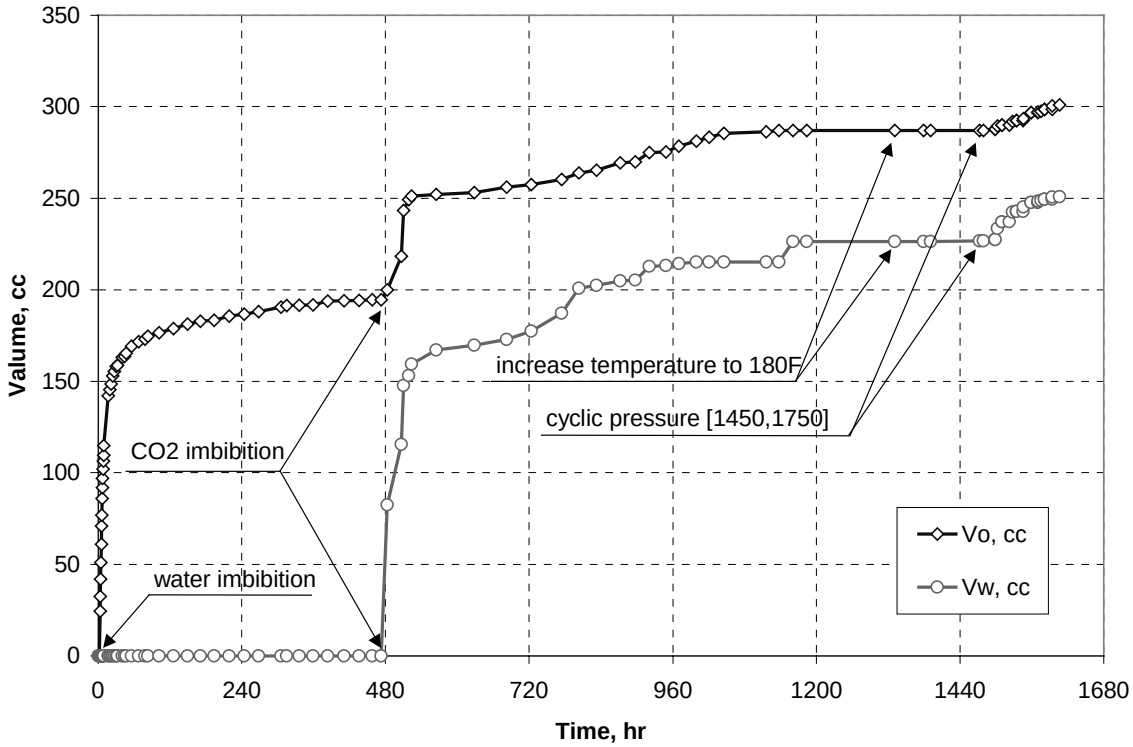

Fig. 5—Oil and water producing history during the experiment.

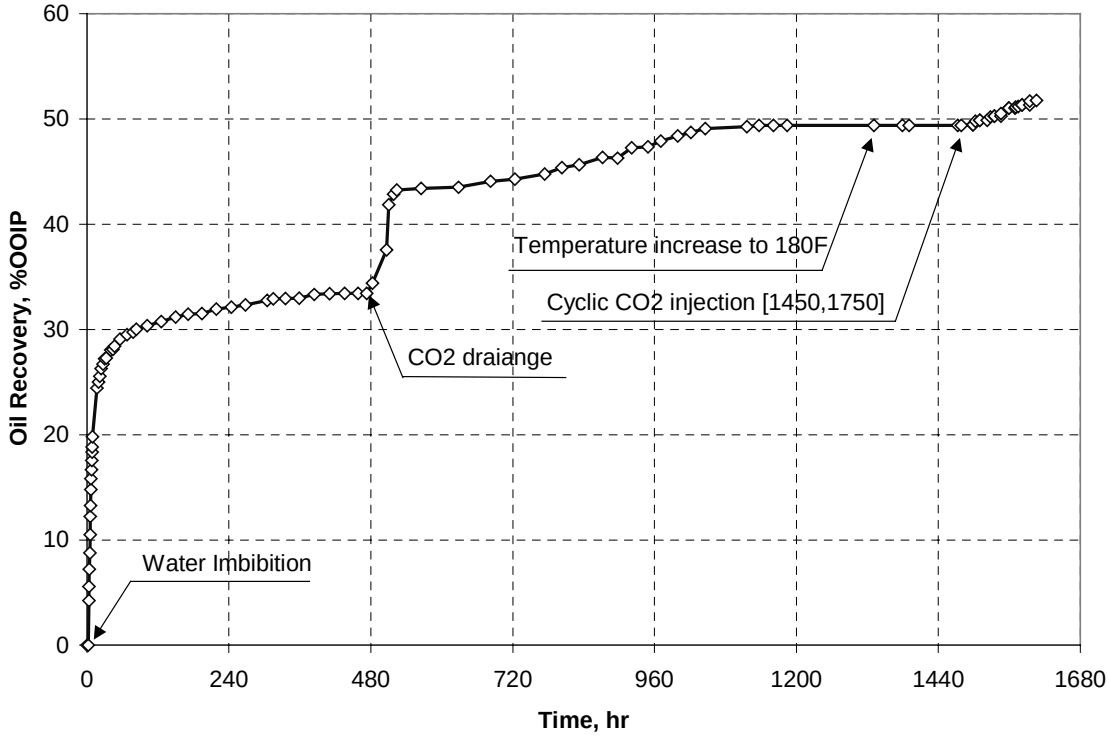

Fig. 6—Oil recovery curve for the whole experiment.

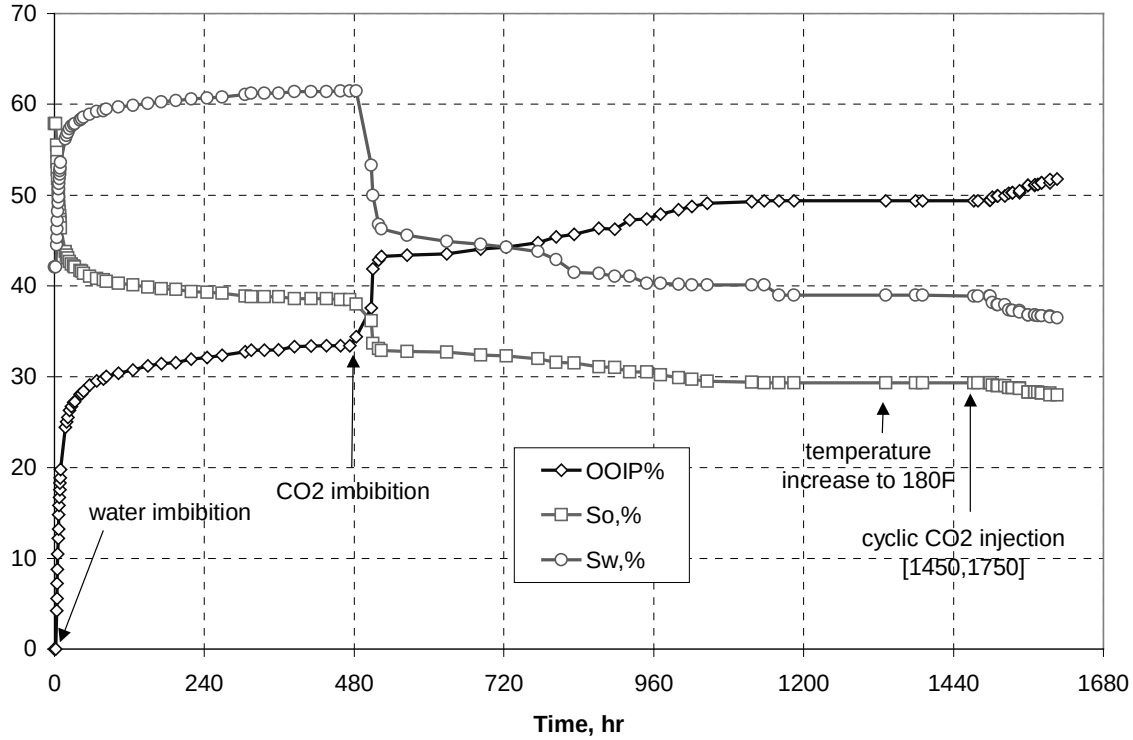

Fig. 7—Oil and water saturation history and oil recovery curve.

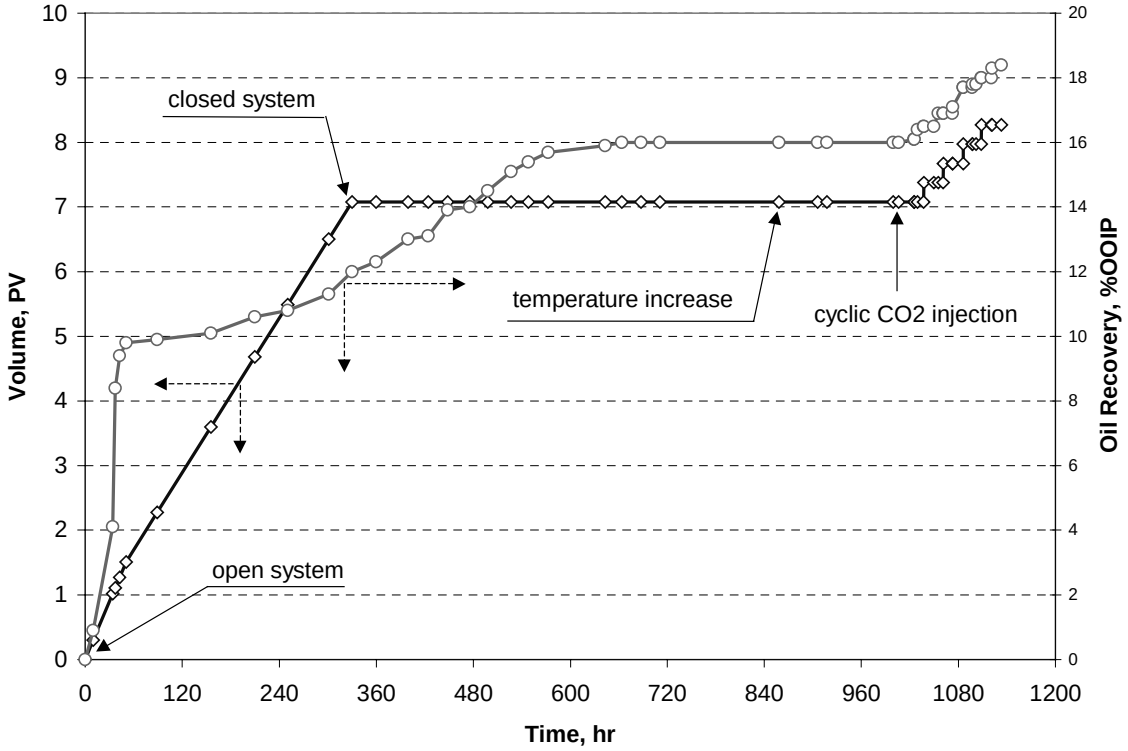

Fig. 8—Oil recovery and volume of CO_2 used during CO_2 drainage.

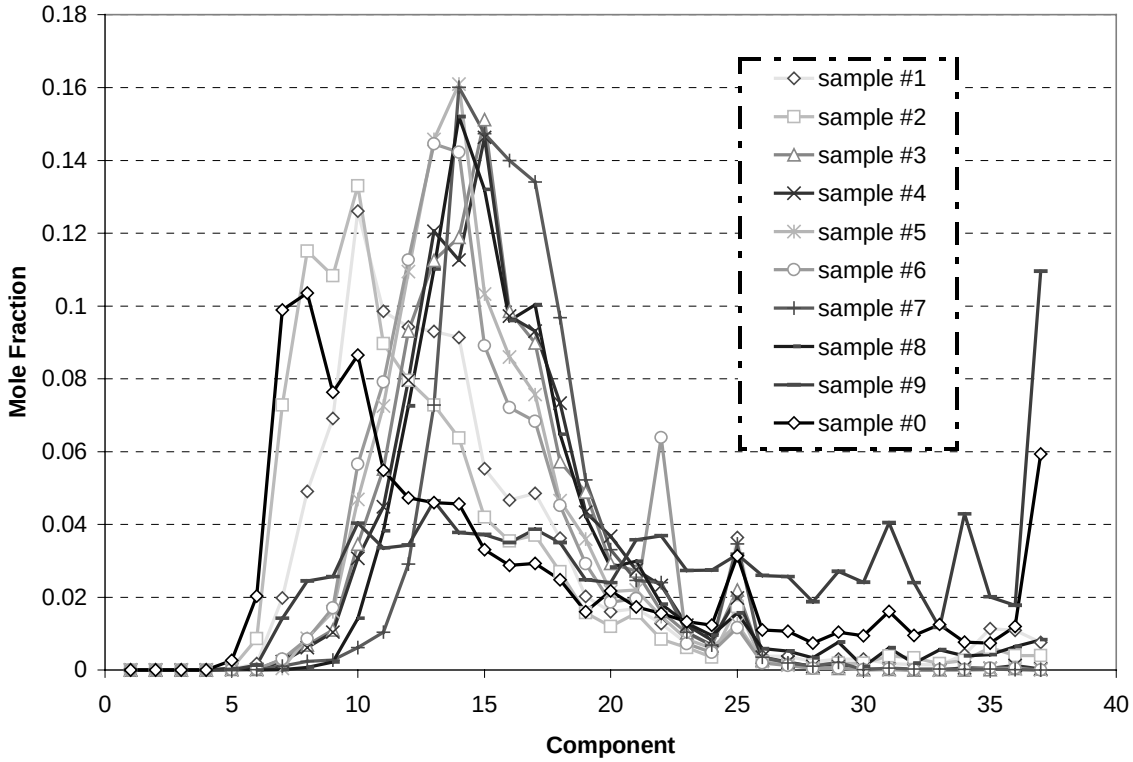

Fig. 9—Mole fraction of oil samples from CO_2 gravity drainage.

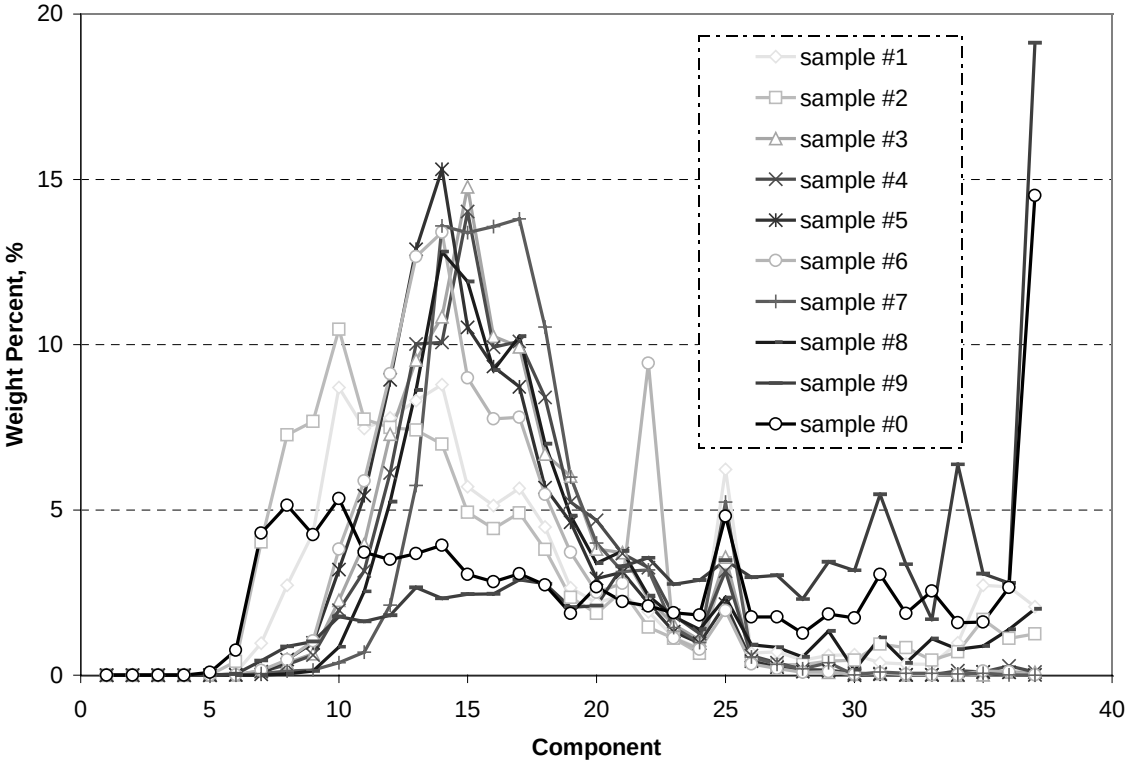

Fig. 10—Weight percent of components of oil samples from CO_2 drainage.

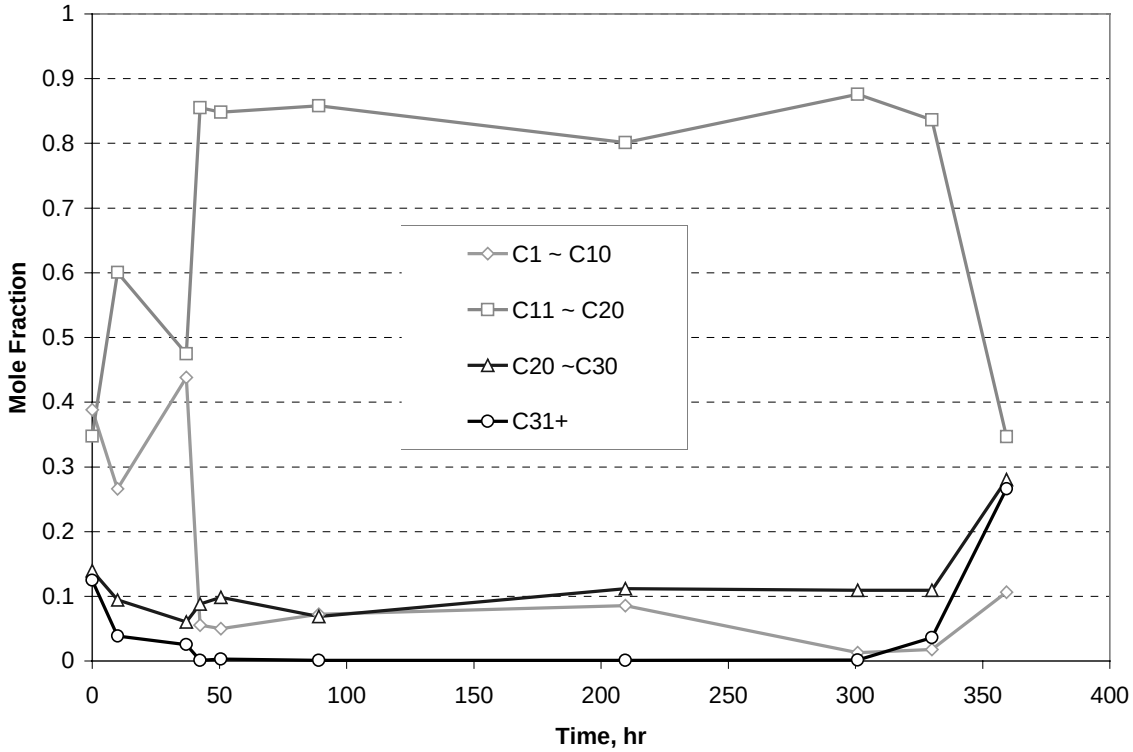

Fig. 11—Mole fraction of component groups of oil samples during CO_2 drainage.

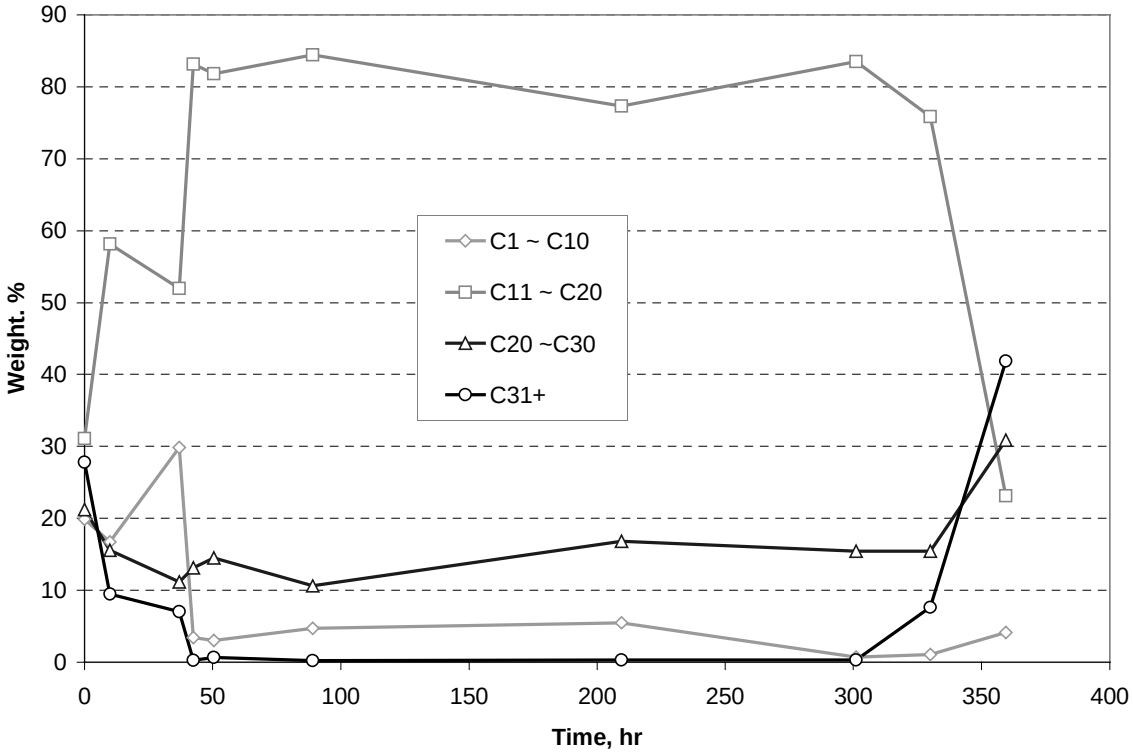

Fig. 12—Weight percent of component group of oil samples during CO_2 drainage.

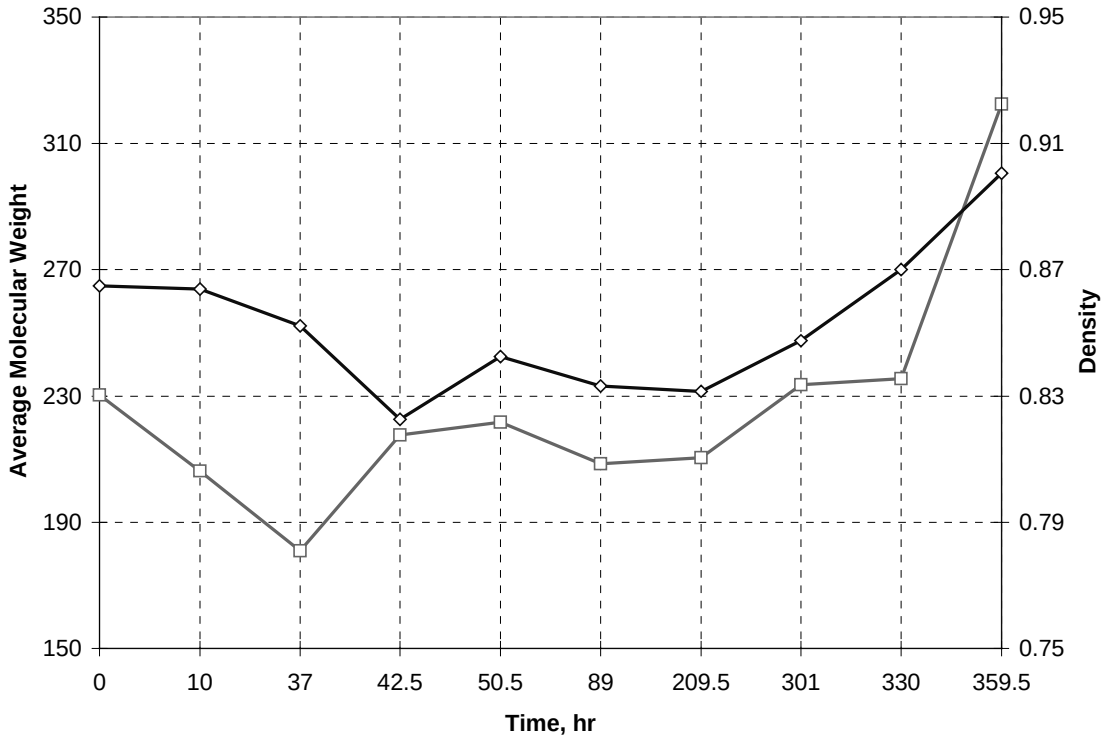

Fig. 13—Average molecular weight and density of oil samples from CO_2 drainage.

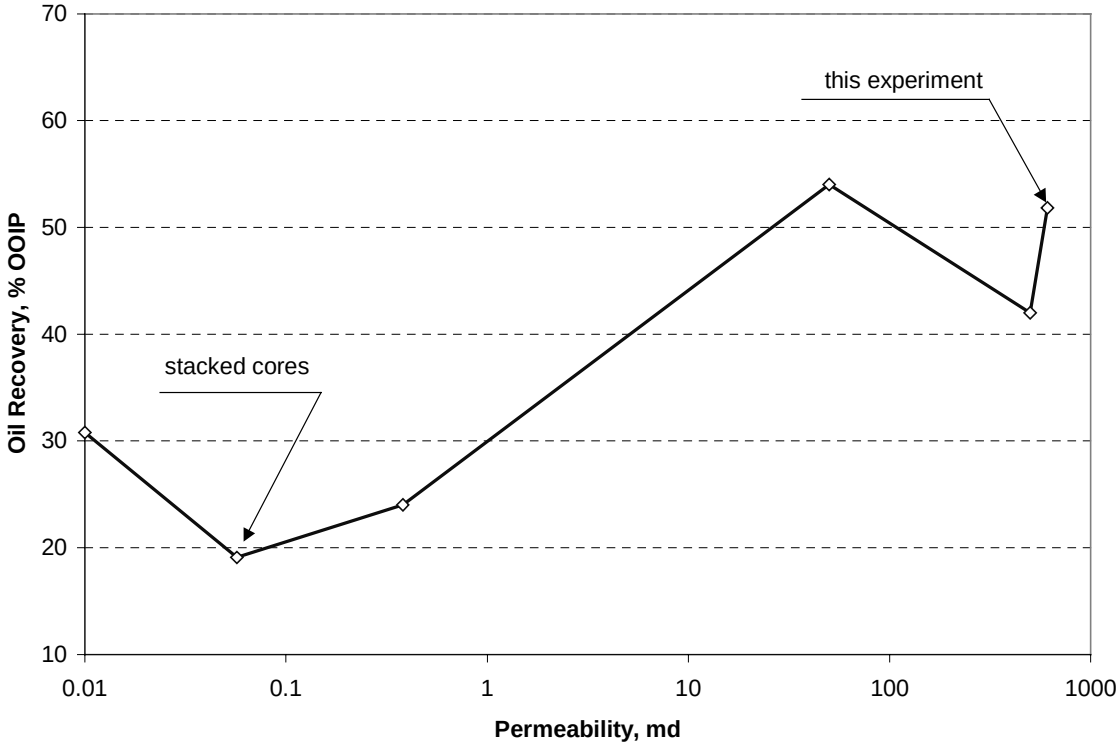

Fig. 14—Oil recovery curves vs. rock permeability of the six experiments.