DOE/BC/14977--10

Quarterly Technical Progress Report

IMPROVED EFFICIENCY OF MISCIBLE CO_2 FLOODS AND ENHANCED PROSPECTS FOR CO_2 FLOODING HETEROGENEOUS RESERVOIRS

DOE Contract No. DE-FG22-94BC14977

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Report Date:	July 20, 1996
Anticipated Completion Date:	April 13, 1997
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Reporting Period:	April 1, 1996, to June 30, 1996

PRRC Report 96-22

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Abstract

Progress has been made in each of the three project areas during this quarter. Each quarter we are highlighting one project area. This quarter, Task 2 is highlighted with expanded details.

Significant progress has been made this quarter in testing the functionalities of the foam-durability apparatus for assessment of foam properties at reservoir conditions. Another surfactant, Alipal® CD-128 at a concentration of 1000 ppm, was used for core flooding experiments. The foam mobility data showed a significant reduction of CO_2 mobility and a favorable mobility dependence on rock permeability.

Two slim tube test series and continuous phase equilibrium were done to examine the effects of pressure, temperature, and oil composition on oil displacement efficiency. A new series of core foam tests were completed to study the effects of flow rate, CO_2 fraction (foam) quality, and rock permeability on foam-flow behavior. We are in the process of moving the foam reservoir simulator MASTER from a workstation to a Pentium PC environment and test MASTER on a 166 MHz Pentium PC.

IFT of CO_2/crude oil has been measured using our pendant drop measurement system at 138°F and pressures from 850 psig to 2200 psig. The CO_2 gravity drainage experiment that is in progress using a 50md Berea core at 138°F and pressures from 1700 to 2000 psig, has reached 48% oil recovery and is continuing to increase. The mathematical model developed previously matches the experimental response accurately.

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Executive Summary

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Introduction

Because of the importance of CO_2 flooding to future oil recovery potential in New Mexico and West Texas, the Petroleum Recovery Research Center (PRRC) has maintained a vigorous experimental program in this area of research for the past sixteen year.

New concepts are being investigated to improve the effectiveness of CO_2 flooding in heterogeneous reservoirs. Research is being conducted in three closely related areas: 1) further exploring the application of selective mobility reduction (SMR) in foam flooding, 2) exploring the possibility of higher economic viability of floods at reduced CO_2 injection pressures, and 3) understanding low interfacial tension (IFT) mechanisms with application to CO_2 flooding in tight vertically fractured reservoirs. Each of these areas have potential of increasing oil production and/or reducing cost in fields presently under CO_2 flood are viewed as candidates for future CO_2 flooding. Also, the results of this research should expand viable candidate fields to include lower pressure and much more heterogeneous or fractured reservoirs.

Results and Discussion

Summary of Progress

Progress was made in each of the three project areas during this quarter and is summarized in the next three paragraphs. Each quarter highlights one project area. An expanded summary of Task 2 is highlighted following the summary paragraphs of the three tasks.

In Task 1, testing the functionalities of the foam-durability apparatus for assessment of foam properties at reservoir conditions was completed and the preliminary results are currently under analysis. Additional experiments were conducted on a series composite core to study the ability of foam to achieve selective mobility reduction in layered systems with capillary contact between the layers. Using surfactant Alipal® CD-128 at a concentration of 1000 ppm, the foam mobility data showed a significant reduction of CO_2 mobility. The data also demonstrated a favorable mobility dependence on rock permeability. The slope of line, as obtained from the regression method, has a value of 0.56, which represents a moderate degree of SMR.

Experimental progress in Task 2 has included two slim tube test series one on a temperature oil and the other on a moderate-temperature oil. Progress also includes continuous phase equilibrium tests at four pressure on a moderate-temperature oil and a new series of core foam tests. The three-phase region found in the lower-temperature system had significant effects near the MMP. The slim tube and continuous phase equilibrium tests complimented each other, demonstrating the significant reduction in hydrocarbon extraction below the MMP. The core foam study improved our understanding of the effects of flow rate, CO_2 fraction (foam quality), and rock permeability on foam-flow behavior. Additional effort was made to move the foam reservoir simulator MASTER from a workstation to a Pentium PC environment and test MASTER on a 166 MHZ Pentium PC.

Progress on Task 3 was made in two areas during this quarter: 1) measurement of interfacial tension (IFT) of a CO_2/crude oil system under reservoir conditions, and 2) CO_2 gravity drainage experiment using whole core and crude oil under reservoir conditions. IFT of CO_2/crude oil has been measured using our pendant drop measurement system at 138°F and pressures from 850 psig to 2200 psig. The IFT decreases with increasing pressure until 1600 psig where IFT stabilizes at about 2 mN/m. Further increase in pressure does not lower the IFT significantly. A CO_2 gravity drainage experiment is in progress using a 50 md Berea core and the same crude oil as tested in the IFT experiments. The test is at 138°F and the pressure has varied from 1700 to 2000 psig. The oil recovery has reached 48% and is continuing to increase slowly. A mathematical model developed previously, has been applied and matches the experimental response accurately.

Additional Details for Task 2

Slim Tube Tests: Lower Temperature Reservoir - Sulimar Queen

Six slim tube tests were completed on a medium API gravity oil from the Sulimar Queen reservoir at 78°F. At this temperature pure CO_2 goes through a saturation pressure at about 950 psia. Earlier studies indicate a three phase region below 950 psia.[1] Slim tube tests were done above, within, and below the three phase region pressures. Figure 1 shows recoveries at 1.2 pore volumes (PV) of CO_2 injected, at CO_2 breakthrough (BT), and at the termination of the test (about 2.0 PV CO_2 injected). In a number of tests CO_2 BT occurred after 1.2 PV of CO_2 was injected. Having CO_2 BT after more than a PV had been injected might seem difficult to image. This is due to CO_2 decreasing in volume by dissolving into the oil and in the three phase region condensing into a liquid phase with a very high concentration of CO_2 and enough dissolved hydrocarbons to reduce the saturation pressure of the CO_2 rich phase. Thus, at the injection pressure and temperature CO_2 in the system has a much higher apparent density then in its pure state. The minimum miscibility pressure (MMP) was found to be about 875 psig which was about 75 psi below the CO_2 pressure of 950 psig at 78°F. Figures 2 and 3 show percentage of oil recovery versus CO_2 injection for the six tests. Figure 2 indicates the injection of CO_2 in terms of PV injected while Fig. 3 is in terms of grams of CO_2 injected. Over a short pressure decrease the PV of CO_2 required for ultimate recovery nearly doubled, while the mass of CO_2 required decreased. This change is found in Figs. 2 and 3. In Fig 2, the 1000 psig test is near the maximum at about 0.95 PV injected, while the 900 psig test requires about 1.90 PV. In Fig. 3, we see that the 1000 psig test required about 100 grams of injection gas and the 900 psig tested required about 45 grams of gas to reach the same recovery level. This should be a common behavior in many lower temperature reservoirs, temperatures below 120°F. Information from this experiments is being used to understand the effect of pressure, temperature, and composition on the oil recovery in CO_2-flooding.

Continuous Phase Equilibrium Experiments

Tests at 1450 and 1850 psig have been completed during this quarter to complement the 2100 and 2450 psig tests reported earlier on Spraberry recombined reservoir oil.[1] Each test was done at 138°F and at a constant pressure. The extraction level of hydrocarbons by the CO_2 phase was significantly lower at 1450 than it was at the three higher pressures. This result was also below the measured MMP of 1550 psig. The density, viscosity and phase compositional information from these tests will be used with PVT and slim tube tests in defining the effect of pressure, temperature, and composition on oil recovery from CO_2 flooding.

Foam Coreflood

Efficient application and evaluation of candidate reservoirs for CO_2-foam processes requires a predictive foam model. To provide input data to the foam model, quantitative information on foam-flow behavior at various foam-test conditions is required. However, some of the information available in the literature is inconclusive and/or in completed. For example, there are discrepancies about foam mobility behavior versus foam quality. Also, fluid flow rate and the foam-flow behavior in the lower range of foam quality (below 50%) has not been reported. The objectives of this study are to further examine the inconsistent information on foam-flow behavior and to explore the lower range of foam quality.

During this quarter, additional foam tests were conducted with a new core designated as core C. The corresponding core properties are listed in Table 1. Foam tests were performed at conditions of 101°F and 2100 psig. As a standard procedure for the foam tests, the core was saturated with brine by injecting more than 100 pore volumes at a flow rate of 5 cc/hr. Then the brine permeability was determined by regression based on several brine injection rates between 5 to 40 cc/hr. Permeability values are listed in Table 2. Baseline experiments were performed by injecting CO_2 and brine simultaneously into the core until a steady-state pressure drop across the core was achieved at each of five gas-liquid volumetric injection ratios (CO_2 fractions, each at three flow rates). Note that a gas-liquid volumetric injection ratio of 4:1 corresponds to a CO_2 fraction of 0.8. After the baseline experiments, the core was flushed with brine to displace CO_2 and then the brine permeability was redetermined. Prior to foam experiments, the core was saturated with surfactant solution at a surfactant concentration of 2500 ppm to saturate the core. The foam experiments were conducted by injecting CO_2 and surfactant solution simultaneously into the core at flow rates and CO_2 fractions similar to the baseline tests done previously. Each test lasted until a steady-state pressure drop across the core was achieved. After the last test, the core was depressurized to the ambient pressure and flushed with brine to completely displace CO_2 and surfactant solution. The core was then pressurized and saturated with brine for a final brine permeability determination. The brine permeabilities were used to determine whether the conditions of the core had been altered during the test series.

The results of the baseline experiments are summarized in Table 3 for total flow rates of 4.2, 8.4, and 16.8 cc/hr and CO_2 fractions of 0.2, 0.333, 0.5, 0.667, and 0.8. At higher CO_2

fractions, the total mobility of CO_2/brine increased with CO_2 fraction, as shown in Fig. 4. However, at lower CO_2 fractions, the affect on total mobility of CO_2/brine was less obvious, and appears to reach a minimum mobility between CO_2 fractions of 0.2 and 0.333. The occurrence of a minimum mobility is consistent with the results of cores A and B reported previously.[1] Figure 5 shows the total mobility of CO_2/brine to be highest at the highest flow rate for CO_2 fractions above 0.5, and lowest at the highest flow rate when CO_2 fraction was lower than 0.5. This was not consistent with the results of cores A and B reported previously[1] that indicated the total mobility of CO_2/brine was higher at 16.8 cc/hr than at 4.2 and 8.4 cc/hr for all tested CO_2 fractions. This issue is currently being studied.

Prior to the foam experiments, the core was injected and saturated with surfactant solution at a surfactant concentration of 2500 ppm to bring the adsorption level to a constant value. A steady-state pressure drop across the core was achieved at a flow rate of 4.2 cc/hr. The surfactant-solution permeability was then determined using the same method used to determine the brine permeability.

The results of the foam experiments are summarized in Table 4 for total flow rates of 4.2, 8.4, and 16.8 cc/hr and CO_2 fractions of 0.2, 0.333, 0.5, 0.667, and 0.8. A CO_2 fraction of 0.5 corresponds to a foam quality of 50%. Examining Fig. 6 shows that the total mobility of CO_2/surfactant solution decreases with increasing CO_2 fraction. However, when comparing resistance factors (mobility of CO_2/brine divided by CO_2/surfactant solution) there appears to be minimum between CO_2 fractions of 0.2 and 0.333, see Fig. 7. This observation was consistent with the results of core B reported previously.[1]

During the foam experiments at a flow rate of 4.2 cc/hr, the CO_2 fraction was decreased to a previously measured value (0.2) but the pressure drop across the core was greater than obtained previously as shown in Table 3. This irreversible behavior was consistent with the results of core B.[1] This irreversible behavior might be due to the effect of the strong foam generated at a higher CO_2 fraction, that did not return to a state corresponding to a lower CO_2 fraction (foam quality). To further investigate this behavior, a second series of foam experiments were initiated after the brine permeability of the core was determined. Even though the core could not be restored to the original permeability, see Table 2, the second series of foam experiments at 4.2 cc/hr for CO_2 fractions of 0.667, 0.5, and 0.2 was conducted. The results are also summarized in Table 3 and plotted in Fig. 6 and indicated in the legend as SAGII. It is clear that, for each CO_2 fraction, the pressure drop across the core was greater than the previous tests, see Table 4. This indicates that the permeability of the core was altered and reduced due to the effects of surfactant and foam. The final brine permeability of the core, determined after the second series of foam tests, confirmed the permeability was decreasing.

In Fig. 8, the total mobility of CO_2/brine was plotted against the CO_2 fraction for cores A, B, and C. It is clear that there was a minimum mobility existed between CO_2 fractions of 0.2 and 0.333 for all the cores tested. The total mobility of CO_2/brine was determined by regression based on tests at total flow rates of 4.2, 8.4, and 16.8 cc/hr, and reported in the 7[th] column of Table 3 and entitled "WAG mobility". In Fig. 9, the total mobility of CO_2/surfactant solution was plotted against the CO_2 fraction for cores B and C at a total flow rate of 4.2 cc/hr. It is clear that for CO_2 fraction ranging from 0.2 to 0.8, the total mobility of CO_2/surfactant solution decreased with increasing CO_2 fraction.

Conclusions

Based on these results and previously reported results, the following conclusions were made:

1. Displacement of oil by CO_2 in a slim tube has its maximum efficiency near the MMP when a three phase region exist in low temperature reservoirs.
2. Continuous phase equilibrium experiments show a dramatic change in the amount of hydrocarbons extracted by the CO_2 rich phase at pressures near the MMP.
3. Total mobility of CO_2/surfactant solution or foam mobility decreased with increasing CO_2 fraction (foam quality), for the tested CO_2 fraction ranged from 0.2 to 0.8.
4. There existed a minimum total mobility of CO_2/brine between CO_2 fractions of 0.2 and 0.333.
5. There existed a minimum foam resistance factor between CO_2 fractions (foam qualities) of 0.2 and 0.333.
6. The effect of flow rate on the total mobility of CO_2/brine is inconclusive.
7. In general, the total mobility of CO_2/surfactant solution increased with increasing total flow rate.

References

1. R. Grigg and D. Schechter, Improved Efficiency of Miscible CO_2 Floods and Enhanced Prospects for CO_2 Flooding Heterogenous Reservoirs, *2nd Annual Report*, DOE Contract No. DE-FG22-94BC14977, July 1996.

TABLE 1. Berea Core Properties

Property	Core C
Length (cm)	2.52
Diameter (cm)	1.27
Porosity	0.20
Pore Volume (cc)	0.65
Initial Brine Permeability (md)	139.28

TABLE 2. Core C permeabilities determined while saturated with brine or a brine-surfactant solution.

Solution	Test period	Permeability, md
Brine	Initial tests	139.3
Brine	After CO_2 mobility tests	143.5
Brine	After baseline experiments	126.0
Surfactant	Saturated with 2500ppm surfactant	121.8
Brine	After 1st series of foam tests	80.1
Brine	After 2nd series of foam tests	59.2

TABLE 3. Summary of Baseline Experiments

Core #	Total Flow Rate (cc/hr)	CO_2 Fraction	Press. Drop (psid)	Total Mobility (md/cp)	Total Interstitial Velocity (ft/day)
C	4.2	0.200	1.43	23.85	12.85
	4.2	0.333	1.49	22.89	12.85
	4.2	0.500	1.46	23.36	12.85
	4.2	0.667	1.46	23.36	12.85
	4.2	0.800	1.29	26.44	12.85
	8.4	0.200	4.17	16.36	25.70
	8.4	0.333	3.92	17.40	25.70
	8.4	0.500	3.40	20.06	25.70
	8.4	0.667	3.19	21.38	25.70
	8.4	0.800	2.44	27.95	25.70
	16.8	0.200	8.63	15.81	51.39
	16.8	0.333	10.96	12.45	51.39
	16.8	0.500	6.47	21.08	51.39
	16.8	0.667	5.35	25.50	51.39
	16.8	0.800	4.07	33.52	51.39

TABLE 4. Summary of foam experiments in chronological order.

Core #	Total Flow Rate (cc/hr)	CO_2 Fraction	Press. Drop (psid)	Total Mobility (md/cp)	Total Interstitial Velocity (ft/day)	WAG Mobility (md/cp)	Resistance Factor
C	4.2	0.200	19.91	1.71	12.85	16.08	9.39
	4.2	0.333	34.04	1.00	12.85	13.17	13.15
	4.2	0.500	34.37	0.99	12.85	20.96	21.12
	4.2	0.667	49.19	0.69	12.85	24.36	35.14
	4.2	0.800	56.01	0.61	12.85	31.66	52.00
	4.2	0.800	77.31	0.44	12.85	31.66	71.77
	4.2	0.200	63.73	0.54	12.85	16.08	30.05
	8.4	0.200	71.64	0.95	25.70	16.08	16.89
	8.4	0.333	73.51	0.93	25.70	13.17	14.19
	8.4	0.500	77.67	0.88	25.70	20.96	23.87
	8.4	0.667	88.97	0.77	25.70	24.36	31.78
	8.4	0.800	94.02	0.73	25.70	31.66	43.64
	16.8	0.200	92.50	1.47	51.39	16.08	10.90
	16.8	0.333	93.48	1.46	51.39	13.17	9.03
	16.8	0.500	105.62	1.29	51.39	20.96	16.23
	16.8	0.667	120.37	1.13	51.39	24.36	21.50
	16.8	0.800	122.59	1.11	51.39	31.66	28.45
	4.2	0.667	66.72	0.51	12.85	24.36	47.66
	4.2	0.500	62.20	0.55	12.85	20.96	38.23
	4.2	0.200	30.19	1.13	12.85	16.08	14.23

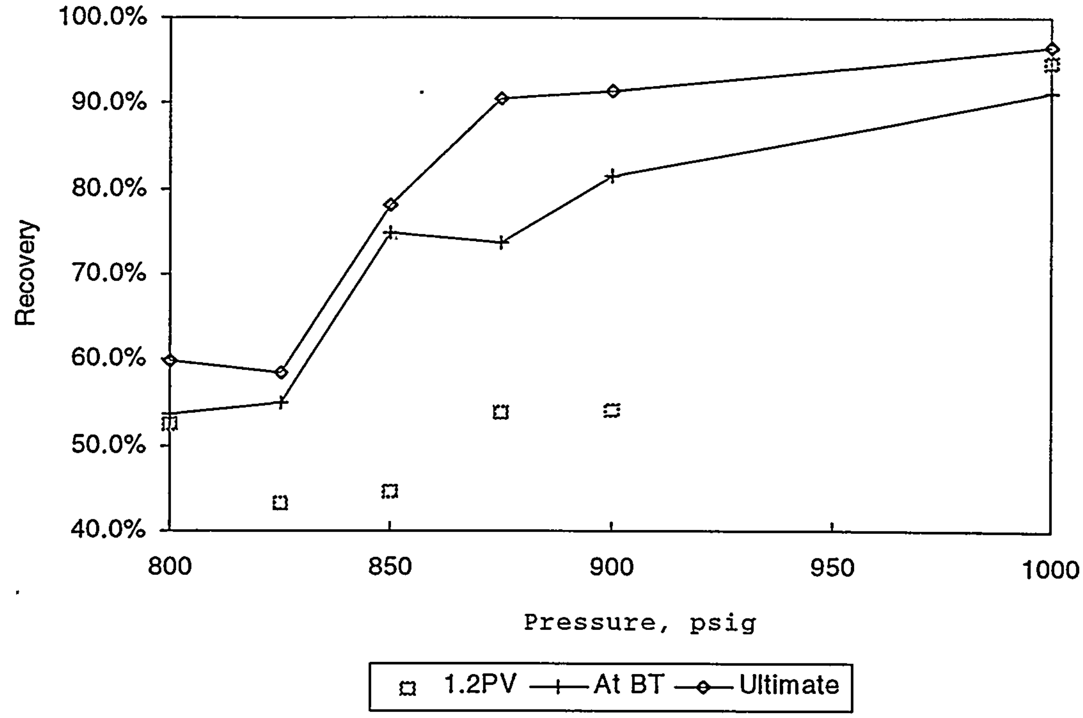

Figure 1. Sulimar Queen Oil recovery after 1.2 pore volume of CO_2 injected, at CO_2 breakthrough and at flood termination versus pressure.

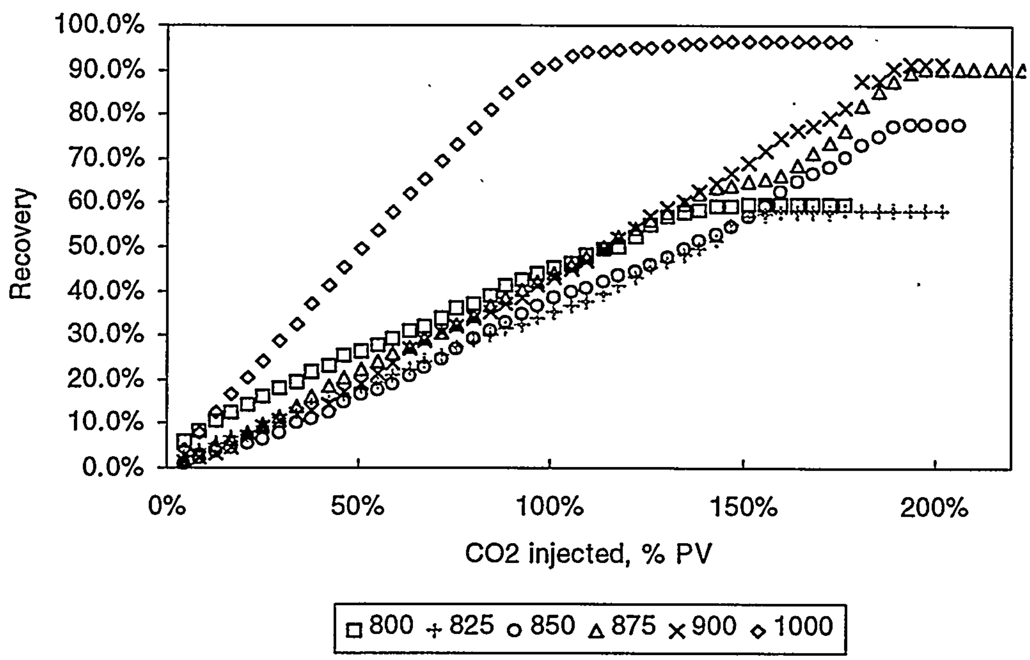

Figure 2. Sulimar Queen oil recovery at each pressure versus percent pore volume of CO_2 injected.

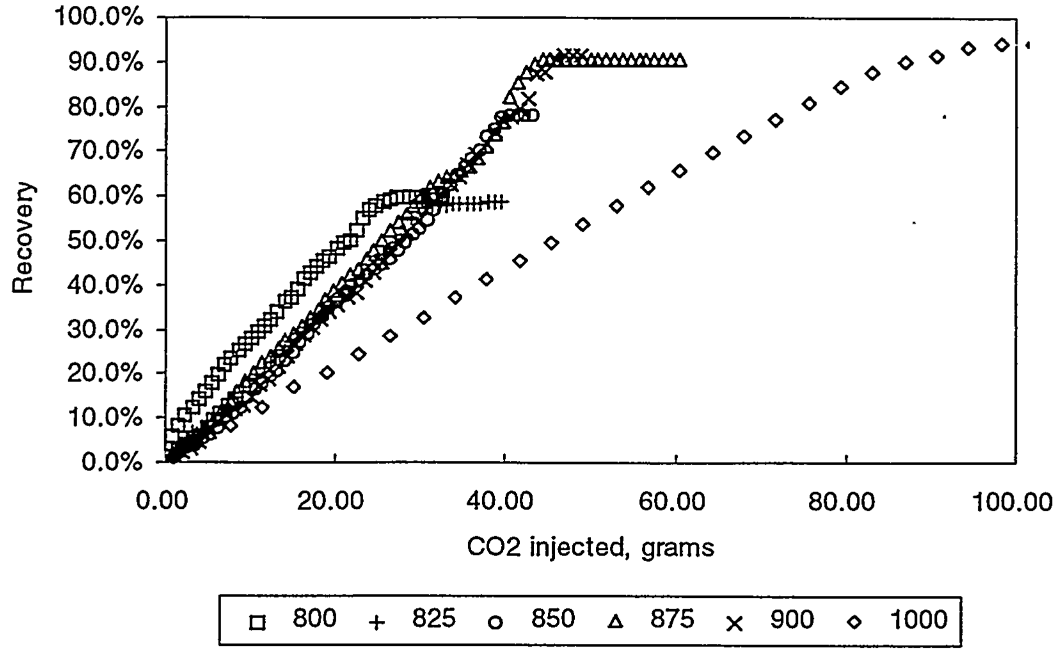

Figure 3. Oil recovery at each pressure versus grams of CO_2 injected.

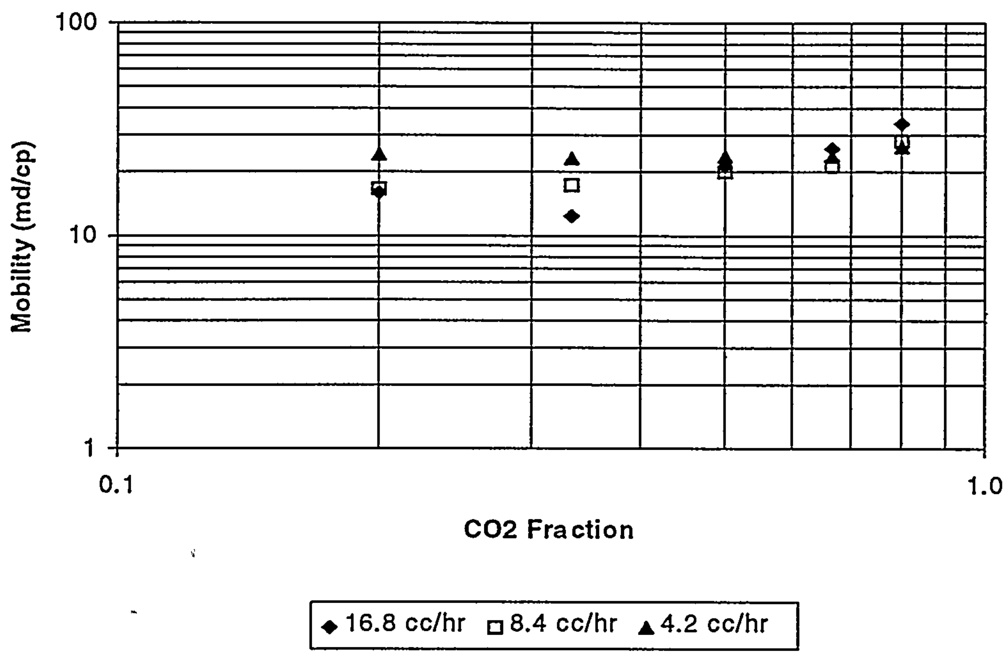

Figure 4. Total mobility of CO_2/brine versus CO_2 fraction in the injection stream at the indicated flow rates.

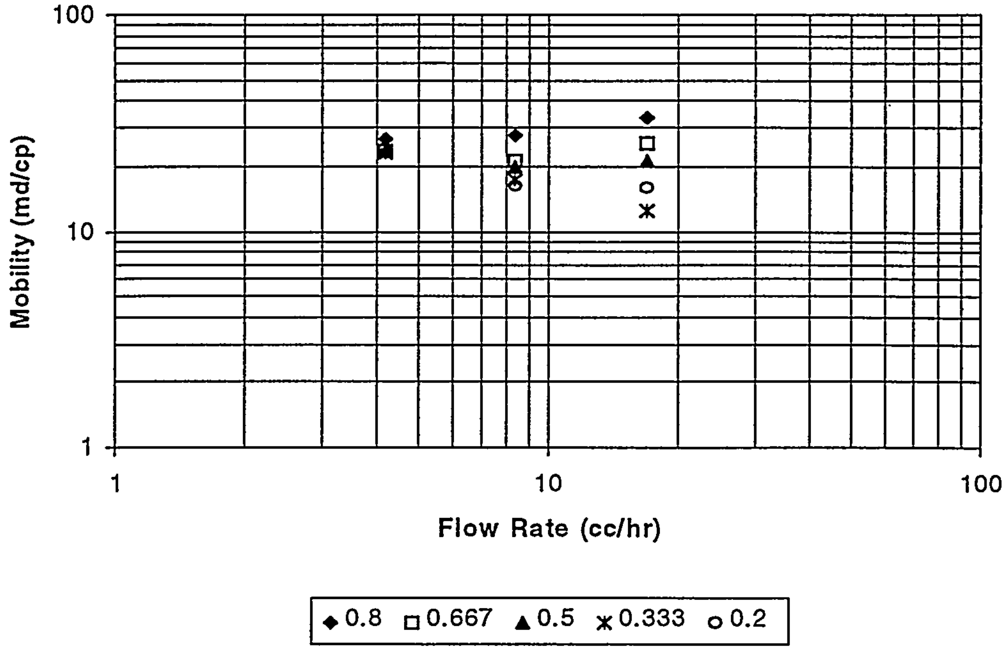

Figure 5. Total mobility of CO_2/brine versus total flow rate at the indicated CO_2 volume fraction of the injected fluid.

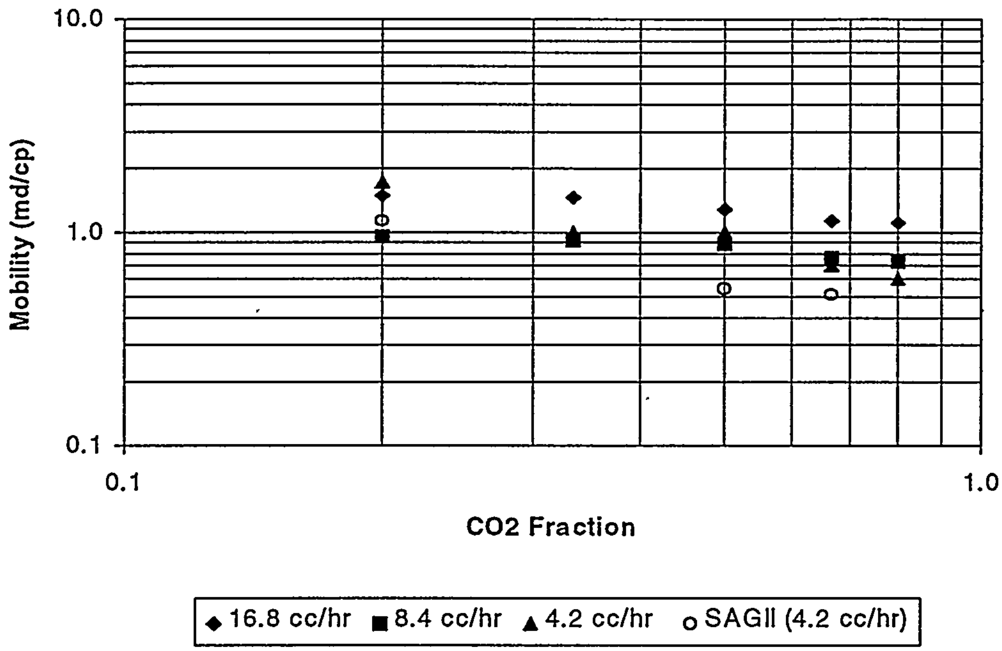

Figure 6. Total mobility of CO_2/surfactant solution versus CO_2 fraction in the injection stream at the indicated flow rates.

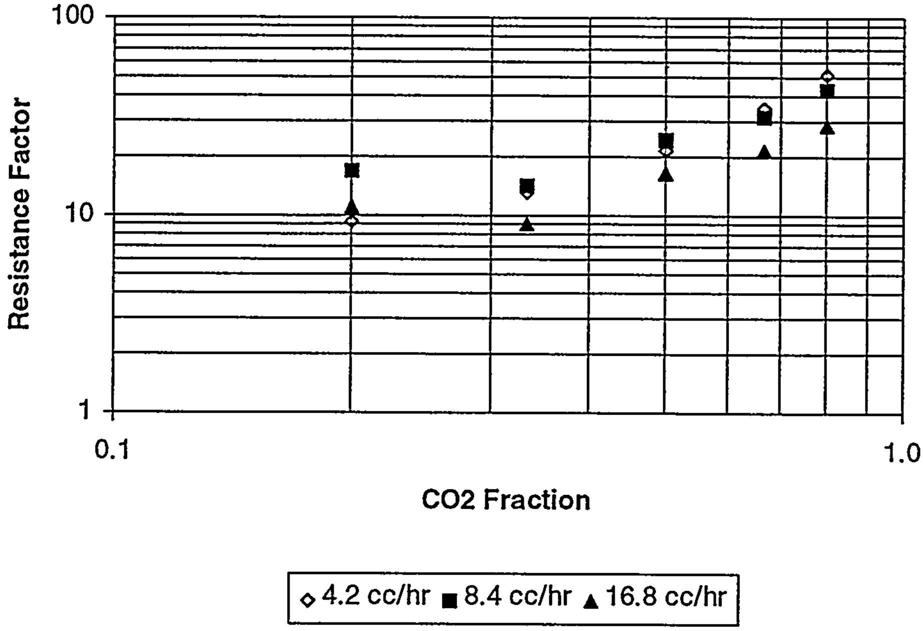

Figure 7. Resistance factor versus CO_2 fraction in the injection stream at the indicated flow rates.

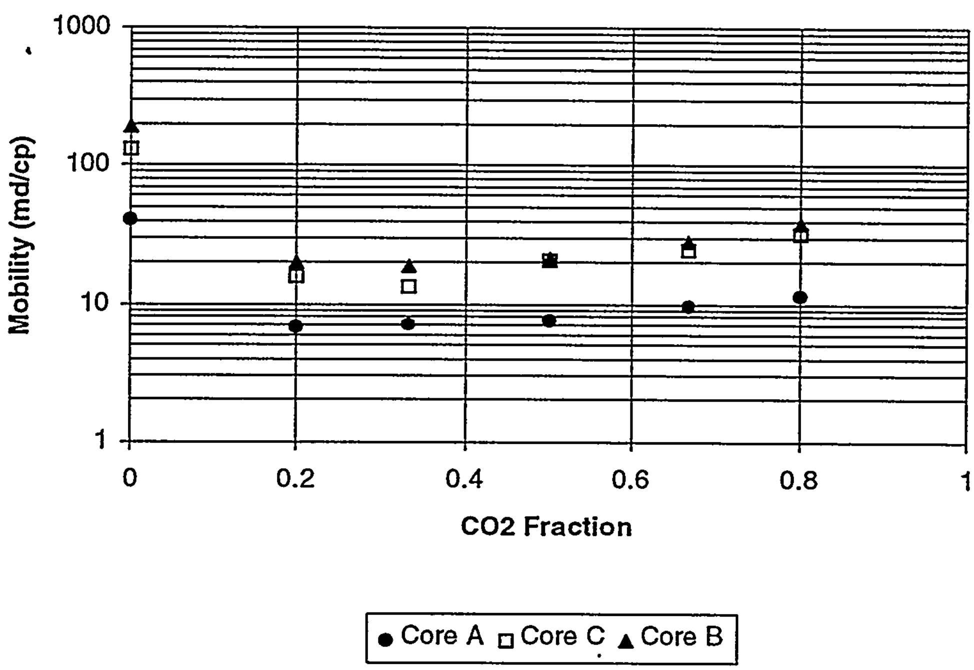

Figure 8. Total mobility of CO_2/brine versus CO_2 fraction in the injection stream for the indicated cores.

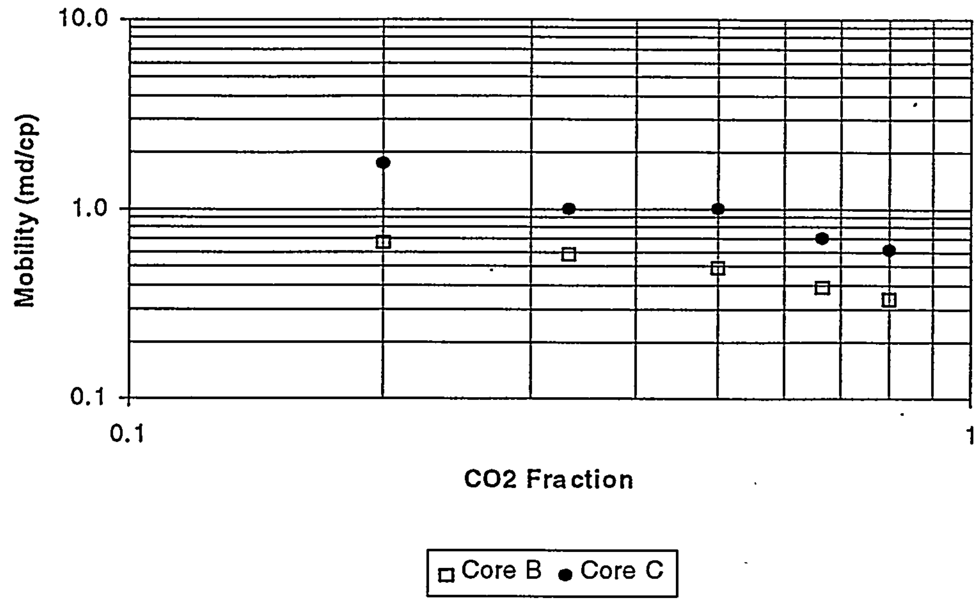

Figure 9. Total mobility of CO_2/surfactant solution versus CO_2 fraction in the injection stream for cores B and C.