Quarterly Technical Report

ADVANCED RESERVOIR CHARACTERIZATION AND EVALUATION OF CO₂ GRAVITY DRAINAGE IN THE NATURALLY FRACTURED SPRABERRY TREND AREA

DOE Contract No.: DE-FC22-95BC14942 - - /0

New Mexico Petroleum Recovery Research Center
New Mexico Institute of Mining and Technology
Socorro, New Mexico 87801
(505) 835 5142

Contract Date: September 1, 1995
Anticipated Completion Date: September 1, 2000

Program Manager: Paul McDonald
Pioneer Natural Resources USA, Inc.

Principal Investigator: David S. Schechter
New Mexico Petroleum Recovery Research Center

Contracting Officer's Representative: Jerry F. Casteel
Bartlesville Project Office

Report Period: October 1, 1997 - December 31, 1997

US/DOE Patent Clearance is not required prior to the publication of this document.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
electronic image products. Images are
produced from the best available original
document.**

ABSTRACT

The overall goal of this project is to assess the economic feasibility of CO₂ flooding the naturally fractured Spraberry Trend Area in West Texas. This objective is being accomplished by conducting 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 CO₂ gravity drainage in Spraberry whole cores. This report provides results of the fourth quarter of 1997 in the fourth area.

Our previous investigations reveal that permeability and water saturation are two of the major factors affecting the efficiency of CO₂ gravity drainage in continuous Berea and Spraberry whole cores. In the fourth quarter of 1997, we investigated the effect of core discontinuity on the efficiency of CO₂ gravity drainage. The core discontinuity was achieved by clamping two cores together to form a stack. The issue was addressed because of the argument that rock matrix blocks may not be always vertically continuous over the pay zone, which may lower gravity drainage efficiency. Our results indicate that the resultant CO₂ gravity drainage efficiency from the core stack is not lower than expected from two separate cores, indicating that capillary continuity was achieved. This is consistent with the increasing evidence of capillary continuity in stacks of cores during gravity drainage experiments.

In order to optimize the CO₂ pilot design in the E.T. O'Daniel Unit of the Spraberry Trend Area, we have scaled up our experimental result from core scale to field-wide level using our newly developed mathematical model presented in the First Annual Technical Progress Report. The results indicate that depending on matrix permeability, water saturation and fracture intensity, significant amount of oil can be recovered from the pilot area by CO₂ flooding in a relatively short time period. Assuming a matrix air permeability of 0.9 md, water saturation of 0.45 and fracture spacing of 1.6 ft in the pilot area, the scaling model predicts incremental oil recovery factor of 0.10 within 2 years after CO₂ injection.

TABLE OF CONTENTS

DISCLAIMER	ii
ABSTRACT	iii
TABLE OF CONTENTS	iv
LIST OF TABLES AND FIGURES	v
EXECUTIVE SUMMARY	vi
INTRODUCTION	1
LABORATORY EXPERIMENTS	1
COMPARISON AND DISCUSSION	2
SCALING OF THE EXPERIMENTAL RESULTS	2
SUMMARY	3
REFERENCES	4

LIST OF TABLES AND FIGURES

Table 1 - Physical Properties of Core Samples Used in the Experiments	5
Table 2 - Calculations of Current Oil Reserve in the Area to be Swept by CO ₂ in the E.T. O'Daniel CO ₂ Pilot	5
Fig. 1 - Oil recovery curves obtained from four CO ₂ injection experiments using continuous cores with different permeabilities and water saturations	6
Fig. 2 - Schematic to illustrate experimental procedure	6
Fig. 3 - Oil recovery curve obtained from a CO ₂ injection experiment using a 0.05 md core stack with an initial water saturation 0.376	7
Fig. 4 - Comparison of oil recovery curves obtained from five CO ₂ injection experiments using cores with different permeabilities and water saturations	7
Fig. 5 - Well locations in the E.T. O'Daniel CO ₂ pilot (not to scale)	8
Fig. 6 - Predicted oil recovery from the E.T. O'Daniel CO ₂ pilot area	8
Fig. 7 - Predicted oil production rate from the E.T. O'Daniel CO ₂ pilot area	9
Fig. 8 - Predicted cumulative oil production from the E.T. O'Daniel CO ₂ pilot area	10

EXECUTIVE SUMMARY

The goal of this project is to test the economic feasibility of CO₂ injection in the naturally fractured Spraberry Trend Area in the Permian Basin. CO₂ injection in naturally fractured reservoirs does not meet classic screening criteria due to the expectation of excessive channeling of low viscosity CO₂ through the natural fractures. However, the number of naturally fractured reservoirs and the low recovery usually attendant with these reservoirs combined with abundance of natural CO₂ sources strongly suggests the necessity of exploring counter-intuitive process options. The success of a CO₂ pilot in the naturally fractured Midale reservoir fortified by laboratory experiments performed under the Department of Energy's Extraction Technology Program were the driving force behind the undertaking of such a risky venture. Both lab and field results indicated that injection of IFT-lowering gas could result in gravity drainage of oil in the matrix blocks if the fractures had sufficient vertical relief and significant density.

In order to optimize the design and maximize the performance of the CO₂ flood pilot, it is vitally important to understand the mechanisms governing CO₂ gravity drainage and identifying factors controlling the efficiency of the process. Our previous investigations reveal that permeability and water saturation are two of the major factors affecting the efficiency of CO₂ gravity drainage in continuous Berea and Spraberry whole cores. In the fourth quarter of 1997, we investigated the effect of core discontinuity on the efficiency of CO₂ gravity drainage. The issue was addressed because of the argument that rock matrix blocks may not be always vertically continuous throughout the pay zone, which may lower gravity drainage efficiency. The core discontinuity was achieved by clamping two cores together to form a stack. Our results indicate that CO₂ gravity drainage efficiency was higher than expected from two separate cores, indicating that capillary continuity was achieved. This is consistent with the increasing evidence of capillary continuity in stacks of cores during gravity drainage experiments.

We have scaled up our experimental results from core scale to field scale using our newly developed mathematical model presented in the First Annual Technical Progress Report. The results indicate that depending on matrix permeability, water saturation and fracture intensity, significant amount of oil can be recovered from the pilot area by CO₂ flooding in a relatively short time period. Assuming a matrix air permeability of 0.9 md, water saturation of 0.45 and fracture spacing of 1.6 ft in the pilot area, the scaling model predicts incremental oil recovery factor of 10% within 2 years after CO₂ injection.

Introduction

During the first and second year of the project, four CO₂ gravity drainage experiments were performed using a 500 md Berea core, a 50 md Berea core, a 0.01 md reservoir core, and a 0.38 md reservoir core from the Spraberry Trend Area. Table 1 summarizes the physical properties of these whole cores. Experimental details were presented in the First Annual Technical Progress Report¹ and the Second Annual Technical Progress Report.² Oil recovery curves are presented in Fig. 1. It is clearly seen from Fig. 1 that the efficiency of the CO₂ gravity drainage decreases with decreasing rock permeability and increasing water saturation.

There exists an argument that matrix blocks in naturally fractured reservoirs may not be vertically continuous due to possible horizontal fractures or thin shale partings in the pay zone, and this matrix discontinuity may affect gravity drainage efficiency.^{3,4} To address this issue, we conducted an experiment using a stack of whole cores simulating vertically discontinuous matrix blocks during the first quarter of the third year. The core stack has an average permeability of 0.05 md and porosity of 10.7 %. A water saturation of 37.6 % was achieved before CO₂ gravity drainage was initiated. The result of the experiment indicates that core discontinuity did not significantly affect the efficiency of CO₂ gravity drainage, which is consistent with other investigations.⁵⁻⁷

In order to optimize the CO₂ pilot design in the E.T. O'Daniel Unit of the Spraberry Trend Area, we have scaled up our experimental results from core to field scale using our mathematical model presented in the First Annual Technical Progress Report.¹ The results indicate that depending on matrix permeability, water saturation and fracture intensity, significant amount of oil can be recovered from the pilot area by CO₂ flooding in a relatively short time period. Assuming a matrix air permeability of 0.9 md, water saturation of 0.45 and fracture spacing of 1.6 ft in the pilot area, the scaling model predicts incremental oil recovery of 10% within 2 years.

Laboratory Experiments

Core Sample. The 2-1/2" whole cores were taken from the 1U Unit of the Upper Spraberry in the horizontal E.T. O'Daniel #28. The first core is core No. 132 taken from depth 7667 to 7668 ft. The second core is core No. 142 taken from depth 7677 to 7678 ft. The received cores had been cleaned. The lengths of the first and the second core are 24.77 cm and 25.08 cm respectively. The porosities of the two cores are reported as 0.109 and 0.097 respectively. Their air permeabilities are 0.16 md and 0.13 md respectively.

Brine. Synthetic Spraberry brine was used in the experiment. Density and viscosity of the brine is 1.08 g/cc and 1.18 cp respectively.

Oil. Spraberry separator oil was used in the experiments. The composition of the oil was obtained from GC analysis. The average molecular weight of the oil is 219.39. The oil sample was tested at 100 °F and 1000 psig. The density is 0.8329 g/cc and the viscosity is

2.956 cp. The Minimum Miscibility Pressure (MMP) of the oil was measured and found to be 1550 psig using slim tube at the reservoir temperature of 138 °F. Details were presented in the First Annual Technical Progress Report.¹

Procedure. The experimental procedure is schematically illustrated in Fig. 2. The unclamped core sections were placed in series and sealed in a core holder with 2,000 psig confining pressure (Fig. 2.a). Brine was then injected into the cores. After brine saturation, porosity and permeability to brine were determined to be 0.107 and 0.05 md respectively. Spraberry oil was then injected into the cores (Fig. 2.b) for establishing an initial water saturation. After establishment of the initial water and oil saturations, brine was injected into the core again to reduce the oil saturation in the core (Fig. 2.c). The purpose of the second water injection was to simulate increasing water saturation as waterflooding proceeds. Water injection was terminated when a water saturation of 37.7% was achieved in the core. The two core sections were then taken out from the core holder and clamped into one stack. Finally, the brine/oil-saturated core stack was placed vertically in a drainage cell and CO₂ was introduced into the drainage cell (Fig. 2.d). Cell pressure was maintained between 1,900 psia and 2,000 psia. The cell temperature was 138°F. Oil recovered during the experiment was collected and recorded.

Results. Both brine and oil have been produced from the core stack. The produced oil is yellow in color. Early experimental results are presented in Fig. 3. It is seen from the data that water saturation has dropped from 0.376 to 0.327, and oil recovery has currently reached 12 % of the original oil in place.

Comparison and Discussion

Figure 4 shows comparison of the newly obtained oil recovery curve from the core stack with those previously obtained from continuous cores. It is seen that although the new reservoir cores are not continuous, CO₂ gravity drainage efficiency in the core stack is not significantly reduced. This may be due to capillary continuity across the interface of the two core sections. In fact, the CO₂ gravity drainage efficiency in the core stack is higher than that in the 0.38 md core during the early time. This is believed to be due to the difference in water saturation in the two experiments.

Scaling of the Experimental Results

The overall goal of this project is to assess the economic feasibility of CO₂ flooding the naturally fractured Spraberry Trend Area in West Texas. This objective will be eventually accomplished by field demonstration in the 10 acre E.T. O'Daniel pilot. However, designing the CO₂ injection in the E.T. O'Daniel pilot area requires predictions of oil production rate, cumulative oil production, and oil recovery in the pilot area. The results of our CO₂ gravity drainage experiments make such predictions possible. The experimental data have been scaled up to pilot dimensions using our newly developed mathematical model⁸ to forecast production performance in the pilot area.

The E.T. O'Daniel CO₂ pilot involves 6 water injection wells, 3 CO₂ injection wells (one of them may be a horizontal well), 3 oil production wells, and 3 log-observation wells. Well location (not to scale) is illustrated in Fig. 5. The area to be swept by CO₂ between the CO₂ injection wells and oil production wells is 1,500 feet long and 300 feet wide, which is 10.33 acres. The current oil reserve in this area is estimated to be about 38,500 STB. Reservoir parameters used in the reserve calculations are summarized in Table 2. The values for water and gas saturations under the current reservoir conditions are estimated based on Elkins' report.⁹

Assuming water saturation $S_w = 0.45$, fracture spacing 1.6 ft, and average matrix permeability 0.9 md, oil recovery, oil production rate, and cumulative oil production from the pilot are predicted and demonstrated in Figs. 6, 7, and 8, respectively. It is seen from these figures that the predicted oil recovery factor is about 0.10 IOIP (oil in place at the beginning of CO₂ injection), oil production rate will drop from 19 STB/D to 12 STB/D in 2 years, and cumulative oil production will reach 4,000 STB after 2 years of production. Obviously, the degree of heterogeneity in the fractures and matrix will determine the economics of CO₂ flooding in Spraberry. The pilot test will determine this information.

Summary

Our previous four experiments on CO₂ gravity drainage using continuous Berea and Spraberry reservoir cores indicate that rock permeability and water saturation are two major factors affecting the efficiency of oil recovery during CO₂ injection into naturally fractured systems. The results of our new experiment using discontinuous Spraberry cores confirm the previous experimental results and indicate that core discontinuity is not a factor significantly affecting the CO₂ gravity drainage process.

Scaling of data from the CO₂ gravity drainage experiments to field pilot dimension predicts that in two years of CO₂ injection, oil recovery factor will be about 0.10 IOIP. Oil production rate will drop from 19 STB/D to 12 STB/D, and cumulative oil production will reach 4,000 STB from the 10.33 acres of area to be flooded after 2 years of production.

References

1. Schechter, D.S.: "Advanced Reservoir Characterization and Evaluation of CO₂ Gravity Drainage in the Naturally Fractured Spraberry Trend Area," First Annual Technical Progress Report, Contract No. DE-FC22-95BC14942, U.S. DOE, PRRC Report No. 96-42 (Dec 1996).
2. Schechter, D.S.: "Advanced Reservoir Characterization and Evaluation of CO₂ Gravity Drainage in the Naturally Fractured Spraberry Trend Area," Second Annual Technical Progress Report, Contract No. DE-FC22-95BC14942, U.S. DOE, PRRC Report No. 97-29 (Dec 1997).
3. Suffridge, E.E. and Renner, T.A.: "Diffusion and Gravity Drainage Tests to Support the Development of a Dual Porosity Simulator," paper presented at the 6th European IOR-Symposium, held May 21-23, 1991 in Stavanger, Norway.
4. Luan, Z.: "Some Theoretical Aspects of Gravity Drainage in Naturally Fractured Reservoirs," paper SPE 28641, presented at the 69th Annual Technical Conference and Exhibition of SPE, held September 25-28, 1994 in New Orleans, Louisiana
5. Horle, T.: "Laboratory Studies of Capillary Continuity in Fracture/Matrix Systems," *SPE Reservoir Engineering* (August 1990).
6. Thomas, L.K.: "Ekofisk Nitrogen Injection," *SPE Formation Evaluation* (June 1991).
7. Conway, P.I., Damm, M., and Andersen, P.M.: "Full Field Dual Porosity Modeling of a Complex Fractured Chalk Oil Reservoir Subject to both Gas and Water Injection," paper SPE 36931 presented at the 1996 SPE European Petroleum Conference held in Milan, Italy, 22-24 October 1996.
8. 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 held in Tulsa, Oklahoma, 22-24 April, 1996.
9. Elkins, L.: "Condensed Report: Spraberry CO₂-Gravity Drainage Telephone Conference Call," PRRC Spraberry Data Base, May 14, 1996.

Table 1 - Physical Properties of Core Samples Used in the Experiments

Core No.	1	2	3	4	5
Core Type	Berea	Berea	Spraberry	Spraberry	Spraberry
Porosity, %	18.1	13	10	11.1	10.7
Permeability, md	500	50	0.01	0.38	0.05
Water Saturation, %PV	35	29.3	38.6	45	37.6

Table 2 - Calculations of Current Oil Reserve in the Area to be Swept by CO₂ in the E.T. O'Daniel CO₂ Pilot

Area to Be Swept by CO ₂	10.33 acres
Net Pay	20 ft
Bulk Volume	9x10 ⁶ ft ³
Porosity	0.1
Pore Volume	9x10 ⁴ ft ³
Water Saturation	0.45
Gas Saturation	0.25
Oil Saturation	0.30
Oil Formation Volume Factor	1.25 rb/STB
Current Oil In Place (COIP)	38,500 STB

Fig. 1 - Oil recovery curves obtained from four CO₂ injection experiments using continuous cores with different permeabilities and water saturations.

Fig. 2 - Schematic to illustrate experimental procedure

Fig. 3 - Oil recovery curve obtained from a CO₂ injection experiment using a 0.05 md core stack with an initial water saturation 0.376.

Fig. 4 - Comparison of oil recovery curves obtained from five CO₂ injection experiments using cores with different permeabilities and water saturations.

Fig. 5 - Well locations in the E.T. O'Daniel CO₂ pilot (not to scale)

Fig. 6 - Predicted oil recovery from the E.T. O'Daniel CO₂ pilot area

Fig. 7 - Predicted oil production rate from the E.T. O'Daniel CO₂ pilot area

Fig. 8 - Predicted cumulative production from the E.T. O'Daniel CO₂ pilot area