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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.

An Experimental Investigation of Gravity Drainage in Artificially Fractured Berea Core

The investigation of oil recovery by CO_2 gravity drainage after water imbibition in Berea core with fracture, initiated during the second quarter of 1999, has been completed. The results obtained from the experiment are presented in this quarterly report. The experiment was initially designed to simulate the actual situation occurring in the naturally fractured Spraberry Trend Area. The results 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 rock permeability decreases and initial water saturation increases.

Introduction

Six experiments have been performed on three Berea and three reservoir cores. The reservoir cores were taken from the Spraberry O'Daniel #37 and Shackelford 1-38A. The physical properties of those whole cores are presented in Table 1.

Table 1. Physical Properties of the Core Samples Used in Previous Experiments

No.	1	2	3	4	5	6
Core Type	Berea	Berea	Spraberry	Spraberry	Spraberry	Berea
Configuration	continuous	continuous	continuous	continuous	stacked	continuous
Length, cm	55.52	55.25	55.0	55.245	24.77 25.08	55.245
Diameter, cm	10.16	10.16	10.16	8.89	6.53 6.58	10.16
ϕ , %	18.7	13.0	10.0	11.1	10.7	22.43
K_{brine}, md	500	50	0.01	0.38	0.057	610.0
S_{wi}, %	35.0	29.3	38.6	45.0	37.6	42.1

. All figures are at the end of the report.

All six experiments were conducted to investigate the efficiency of CO_2 gravity drainage and the effect of initial water saturation, S_{wi}, on the efficiency. The fifth experiment, which used a stack of two 2.5 in. Spraberry cores, was also used to investigate the effects of core discontinuity and impermeable layers at the top and bottom of pay zones on recovery efficiency. The sixth experiment was used to investigate the effect of water imbibition followed by CO_2 gravity drainage on the efficiency. The results are summarized in Table 2. It should be noted that, for the sixth experiment, the initial water saturation and the initial oil and water in place were the values before CO_2 gravity drainage after water imbibition, and that recovery and time were the values obtained during CO_2 gravity drainage process.

Table 2. Results Obtained from Previous Experiments

No.	1	2	3	4	5	6
S_{wi}, %	35.0	29.3	38.6	45.0	37.6	66.5
S_{or}, %	37.5	32.5	42.5	41.8	50.5	28.0
IOIP, cc	544.5	411.1	273.8	209.3	111.0	336.3
IWIP, cc	293.2	171.2	172.1	171.3	67.0	667.7
Recovery, %	42.0	54.0	30.8	24.0	19.1	18.5
Time, day	6	220	190	167	331	36

Figure 1 summarizes the results (oil recovery curves) of all the six experiments. Oil recovery versus rock permeability and oil recovery versus initial water saturation are given in Figs. 2 and 3. It is clearly seen from the figures that the efficiency of CO_2 gravity drainage decreases as initial water saturation increases. Core discontinuity and impermeable layers at the top and bottom of the pay zone could affect the efficiency of CO_2 gravity drainage, as can be seen by comparing the result of the fifth experiment (stacked cores, K= 0.057 md and Swi = 0.376) with that of the third experiment (continuous core, K= 0.01 md and Swi = 0.386). Figures 2 and 3 show that the effect of initial water saturation on oil recovery is more pronounced than the effect of rock 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 Schecter and Guo (1996).[2] 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, more experiments have been and are being performed to model the actual field experience of first waterflooding and then CO_2 injection in the naturally fractured Spraberry Trend Area. The objective of the experiments is to investigate the effect of water imbibition followed by CO_2 gravity drainage on oil recovery under reservoir conditions. The experiments were initially designed to use Berea cores and then Spraberry core. As the experiment on the Spraberry

core has not been completed at the time of this writing, only the results obtained from the experiment of an artificially fractured Berea core are presented in this report.

Laboratory Experiment

Materials

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

Oil. Spraberry dead oil was used in the experiment. 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 at room temperature (26°C) and ambient pressure (12.6 psia).

Core sample. A 4 in. (10.16 cm) Berea core with the length of 9.625 in. (24.45 cm) was used in this experiment. The total bulk volume is 1971.34 cm^3 and the pore volume is 348.0 cm^3. Thus the calculated porosity is 17.65 %. The permeability to brine of the core was measured at various constant pressures and flow rates at room temperature (26°C) using synthetic Spraberry brine (see Table 3). The average permeability to brine is about 210.0 md.

Table 3. Results of Permeability Measurement

Constant Flow Rate	Q, cm^3/hr	500	1000	1500	2000
	Δp, psi	3.5	6	8	11
	k, md	147.25	196.3	220.9	214.2
Constant Pressure	Δp, psi	10	15	20	25
	Q, cm^3/hr	1670	2740	3570	4410
	k, md	196.8	215.2	210.3	207.8

Experimental Results

Figure 4 schematically illustrates the setup used in this experiment. Basically, it consists of a drainage cylinder, a visual cell for collecting produced fluids, 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 from the core. The whole system was in an oven with temperature of 58.9^{o}C (138°F).

Core preparation. The Berea core was put into a core holder and cleaned following the procedure described in the previous reports.[1,3] After being cleaned, it was taken from the core holder and put into an oven with high temperature for drying. The core was then oriented vertically in a core holder and air removed from the top of the cell using a vacuum pump. Synthetic Spraberry brine was allowed to enter from the bottom of the cell

due to the vacuum pressure (-12 psi). After the core was saturated with brine, more brine was flushed into the core. Permeability was measured at this stage.

Spraberry dead oil was then injected into the core from the top of the core at 50 cm^3/hr. Oil broke through when 215 cm^3 of brine was produced. The total amount of dead oil injected into the core was 1002.5 cm^3 (2.88 PV). The volume of brine produced from the core was 264 cm^3 in total. Thus, the initial water saturation, S_{wi}, and the initial oil saturation, S_{oi}, were 24.14% and 75.86%, respectively.

The core was aged five days at high temperature. It was then split (artificially fractured) into two pieces and a fracture was formed (see Fig. 5). The fracture went through the middle on one side, and deviated from the center about one-fourth on the other side. The two ends of the core were then sealed with PT-7 epoxy, to leave only the fracture open for fluid flow.

Water Imbibition. Water imbibition was performed at reservoir temperature for 28 days. The core holder was placed vertically in the oven. Brine was injected from the bottom at the rate of 10 cm^3/hr and then 50 cm^3/hr for the last 13 days. The backpressure was above 1750 psia. A total of 13.7 cm^3 oil was produced, which was 5.19 % IOIP (see Fig. 6). Oil saturation deceased from the initial saturation, 75.86%, to 71.93%, and water saturation increased to 28.07 %.

CO_2 gravity drainage. CO_2 gravity drainage was conducted at a temperature of 138°F for 38 days. The core holder was placed vertically in the oven. At first, the backpressure was set at 1750 psi and later increased to 1950 psi. CO_2 was pumped into the core from the top. The flow rate was 10 cm^3/hr at first and then 5 cm^3/hr 6 hours later. After CO_2 gravity drainage was performed for 806 hours, the pressure in the system was decreased by gradually decreasing the backpressure from 1950 psi to 0 psi (see Figs. 7 and 8).

The total volume of oil produced from the core was 72.5 cm^3 and the total volume of water produced was 98.6 cm^3 (see Fig. 7). The oil recovery with CO_2 gravity drainage was 28.97% IOIP (see Fig. 8). The residual oil saturation was 51.1%.

The total oil recovery is 34.2% during water and CO_2 gravity drainage.

Analysis and Discussion

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

This experiment was performed in a Berea core with a fracture, which was artificially fractured after being saturated with brine and dead Spraberry oil. All the surfaces of the core were sealed or isolated except for the fracture. So water imbibition and CO_2 gravity drainage occurred only in the fracture. The results obtained from CO_2 gravity drainage are plotted on the oil recovery curve diagram (see Fig. 9). In the figure, a water saturation

(28.1) after water imbibition is used and the oil recovery for this experiment is obtained during CO_2 gravity drainage. It can be seen that the oil recovery is lower than that obtained from the 47.7 md Berea core with similar initial water saturation. The reasons could be that CO_2 contacted the core only through the fracture and two-phase flow occurred in the core. It should be noted that the oil recovery increased rapidly on the right end of the curve due to the decrease of the system pressure.

The results obtained from this experiment are also plotted on the diagrams of oil recovery versus rock permeability and oil recovery versus initial water saturation (see Figs. 10 and 11). It appears that there is no simple relationship between oil recovery and rock permeability. It can be seen, however, that oil recovery from Berea core is higher than that from Spraberry core, and that oil recovery from high permeability core is larger than that from low permeability core, depending on the wettability of core samples. A good correlation exists between oil recovery and initial water saturation, which can be clearly seen from Fig. 11. There are two exceptions, however. One is the experiment on the stacked Spraberry cores, and the other is this experiment. More experimental investigation must be performed.

Some oil samples were taken during CO_2 gravity drainage and analyzed using gas chromatography. The results are plotted in Fig. 12. Most middle components (C_{11} ~ C_{20}) were extracted by CO_2, which is consistent with the conclusion presented in last quarterly report.

Summary

This was the first experiment to investigate CO_2 drainage on an artificially fractured core, in order to model CO_2 gravity drainage in a fractured reservoir. To better understand the CO_2 gravity drainage mechanism in a fractured reservoir, more experiments need to be conducted. The results obtained from this experiment basically show that the oil recovery of CO_2 gravity drainage in this situation is lower. The results from this experiment provide more evidence for supporting our previous conclusions, which are:

1. CO_2 gravity drainage could significantly enhance oil recovery after waterflooding in the naturally fractured Spraberry Trend Area.
2. Water imbibition followed by CO_2 injection could be more efficient than injecting CO_2 alone, depending on the wettability.
3. The efficiency of CO_2 injection decreases as rock permeability decreases and initial water saturation increases.
4. Initial water saturation may have more effect on oil recovery than does rock permeability.

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.
3. Hujun Li, "Experimental Investigation of CO_2 Gravity Drainage in Spraberry and Berea Whole Core," the Fifth Naturally Fractured Reservoir Symposium, Socorro, NM, October 28, 1999.

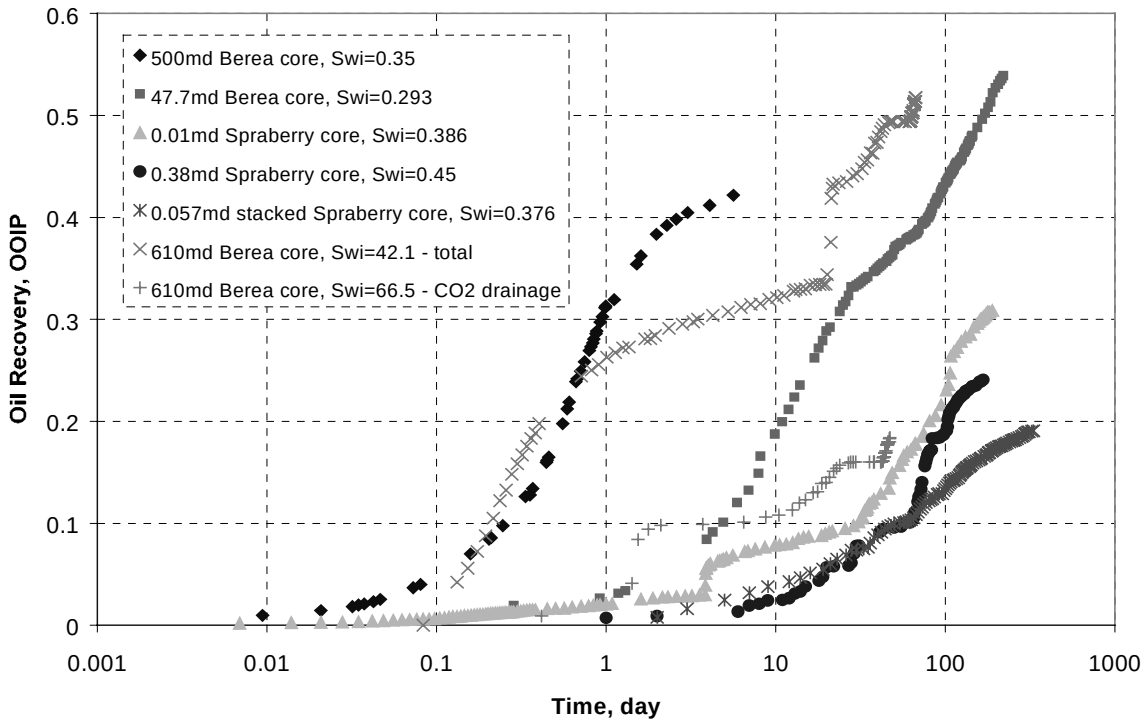

Fig. 1. Oil recovery curves from the previous experiments with different rock permeabilities and initial water saturations.

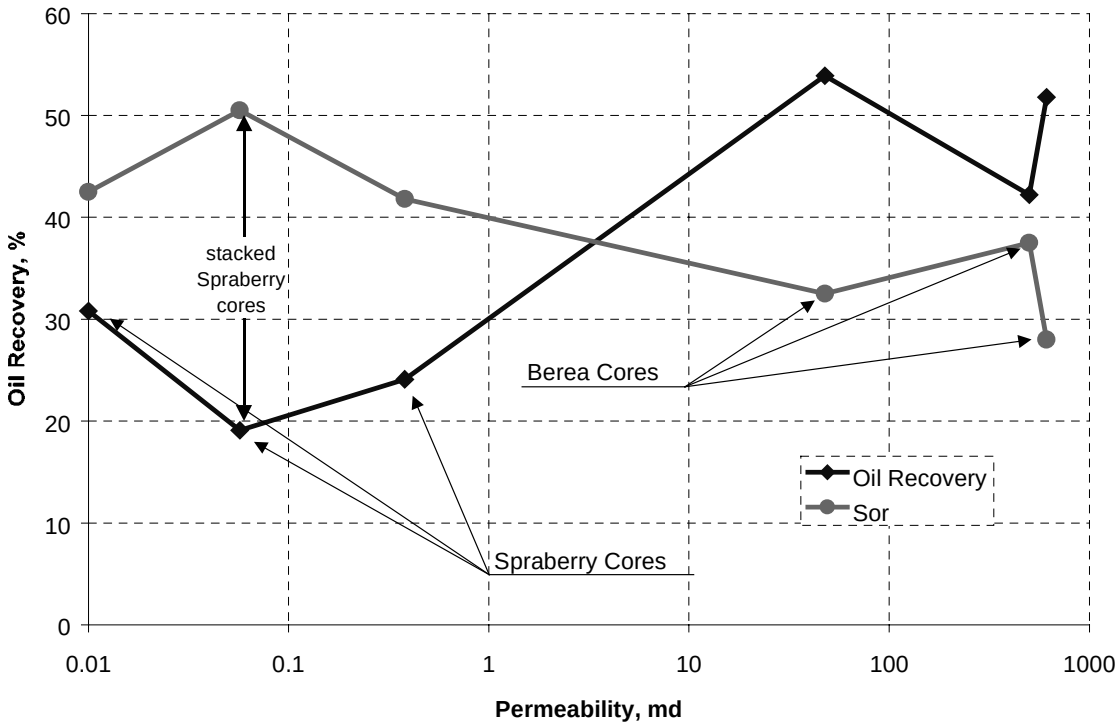

Fig. 2. Effect of permeability on oil recovery of CO_2 gravity drainage.

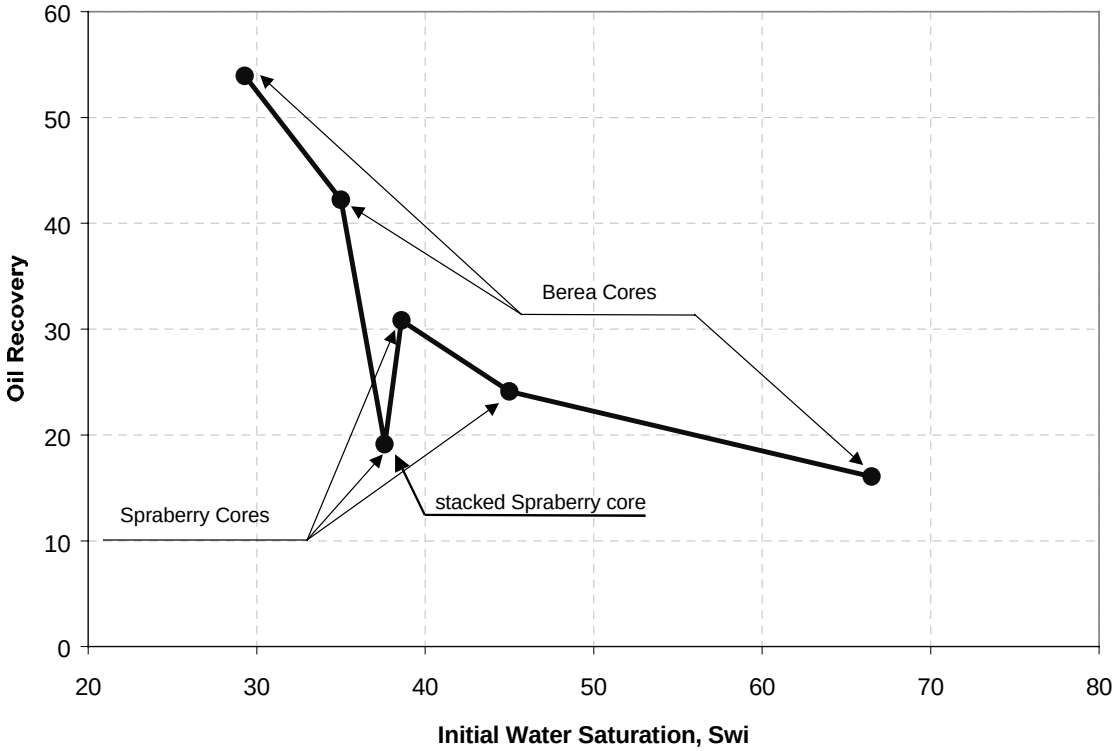

Fig. 3. Effect of initial water saturation on oil recovery of CO_2 gravity drainage.

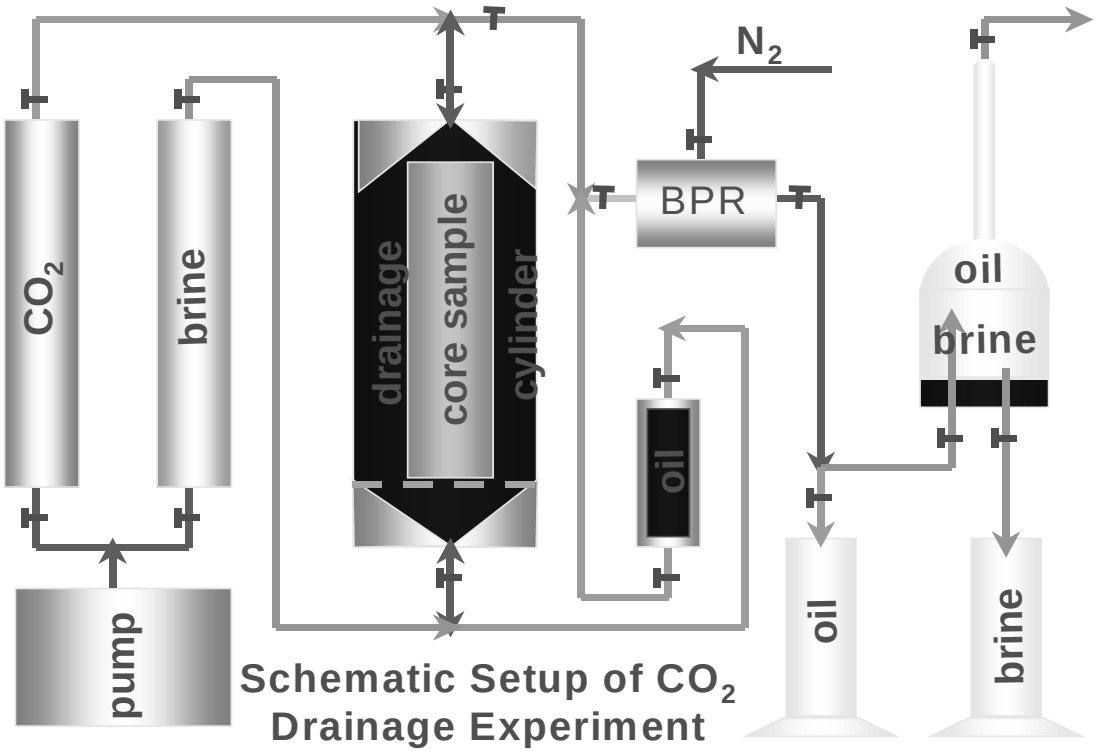

Fig. 4. Setup for water and CO_2 gravity drainage experiment.

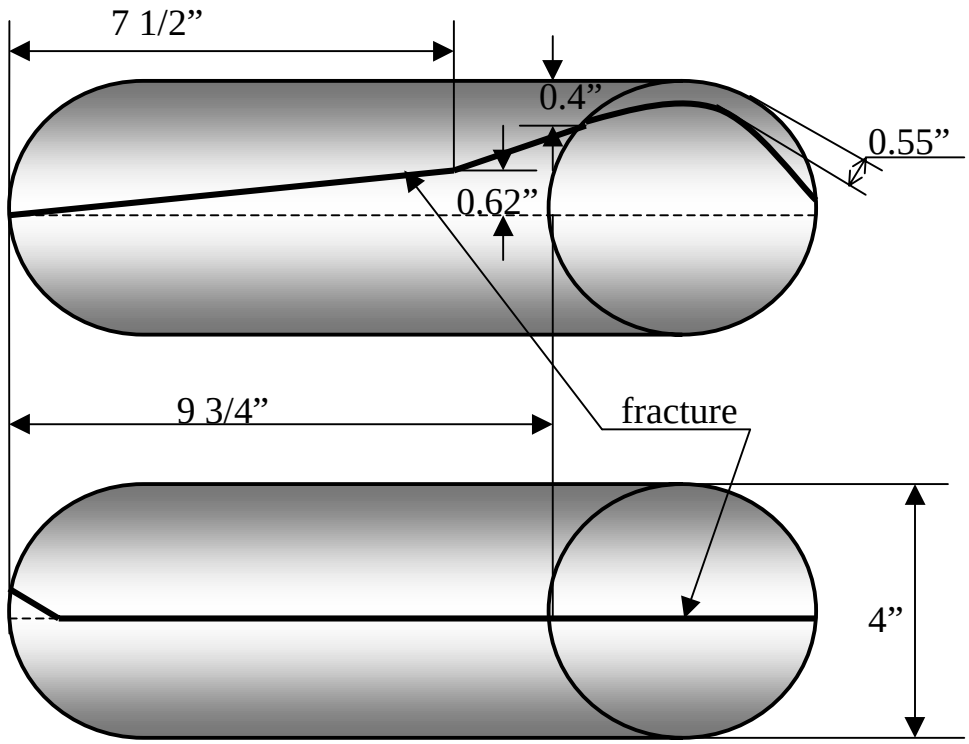

Fig. 5. Sketch of the Berea core with a fracture.

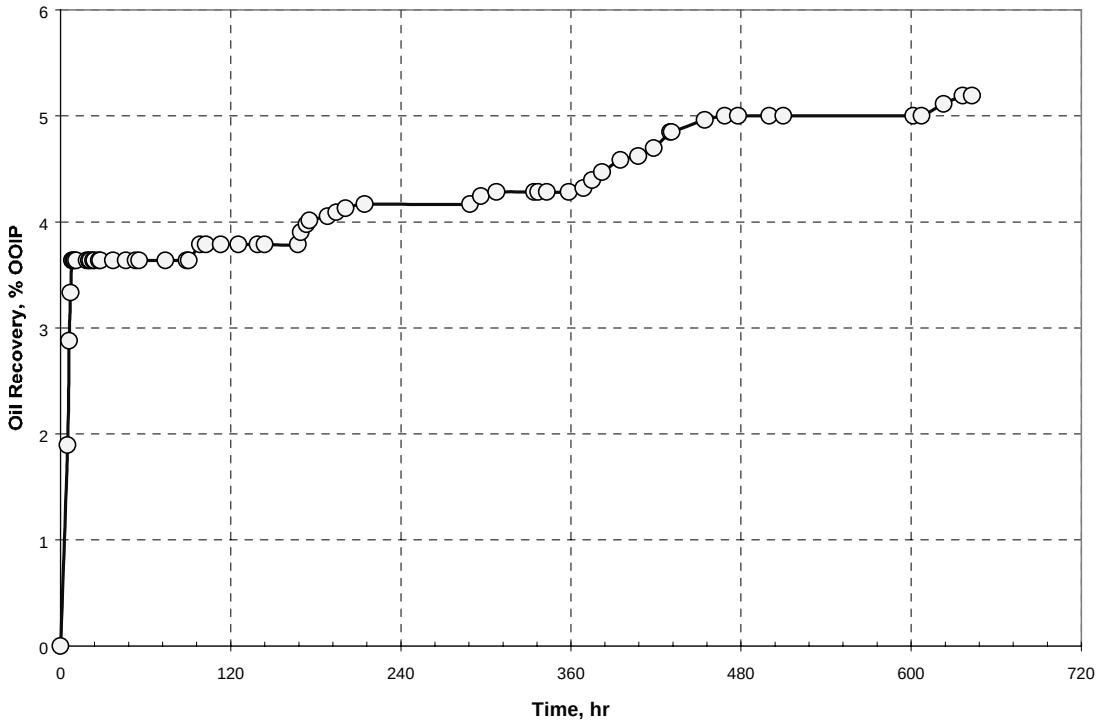

Fig. 6. Oil recovery curve during water imbibition.

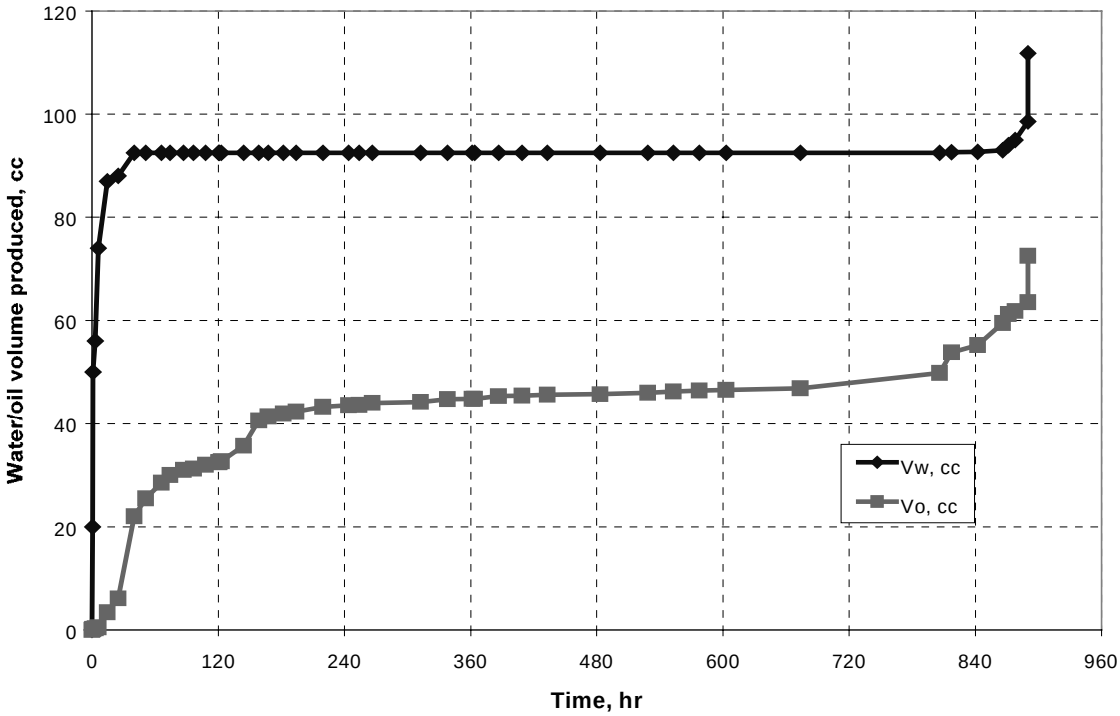

Fig. 7. Water and oil production history during CO_2 gravity drainage.

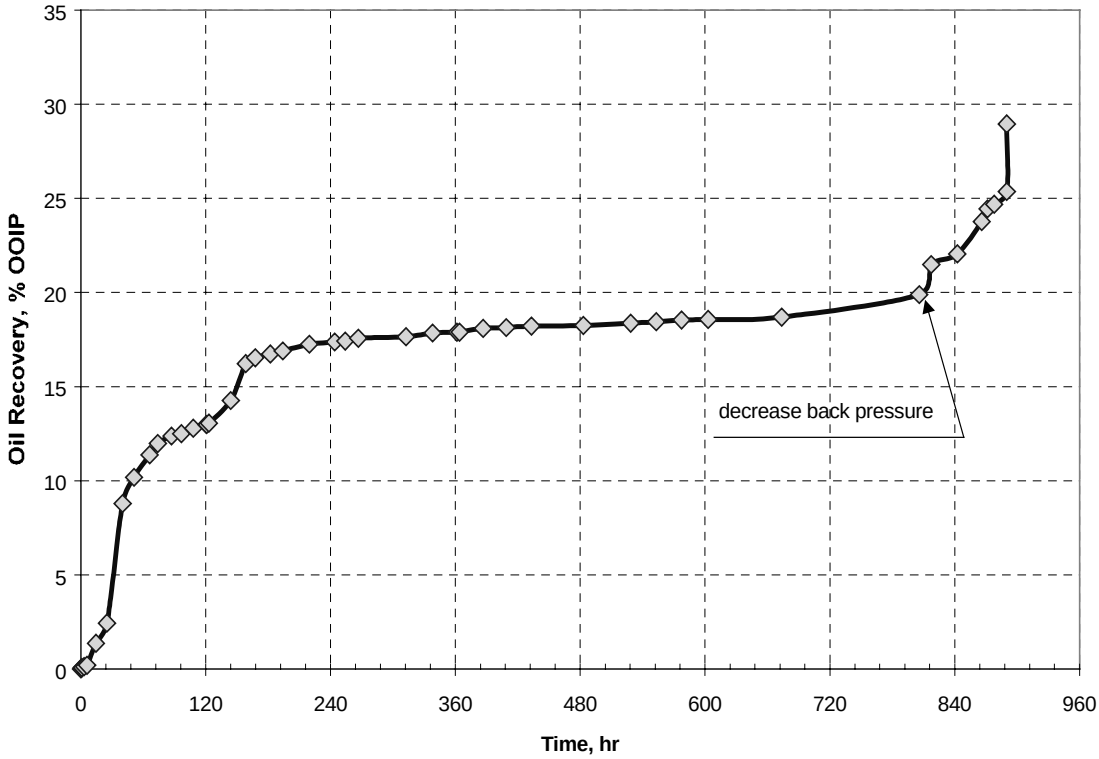

Fig. 8. Oil recovery during CO_2 gravity drainage.

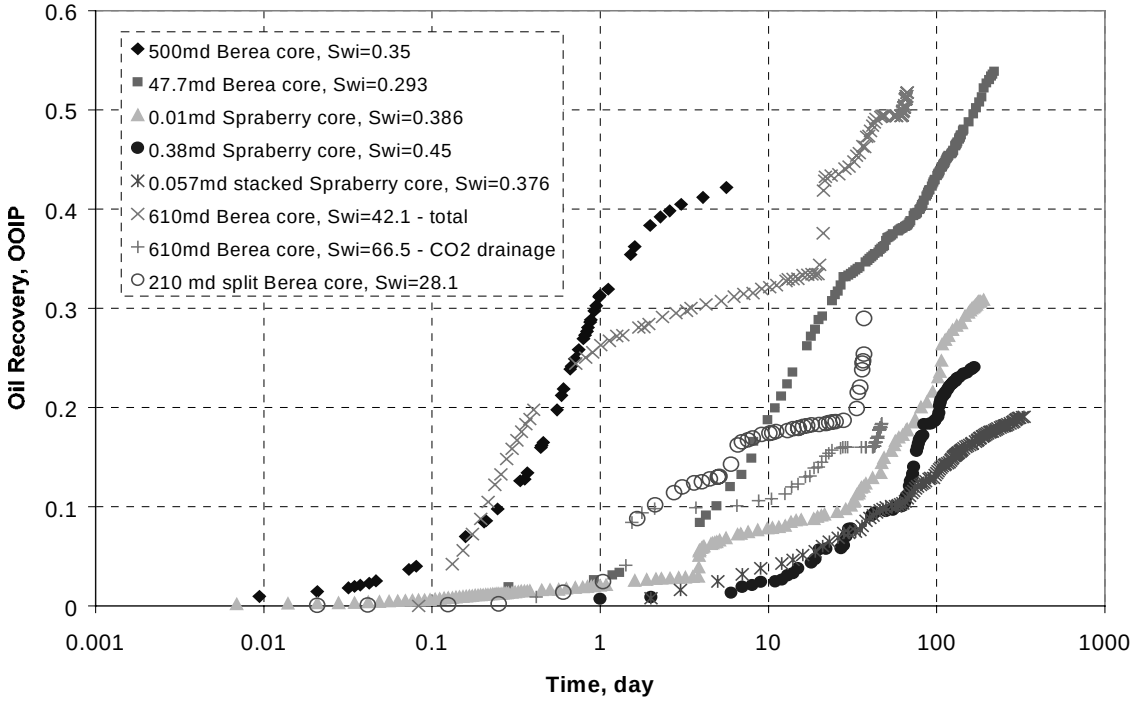

Fig. 9. Oil recovery curves with different rock permeabilities and initial water saturations.

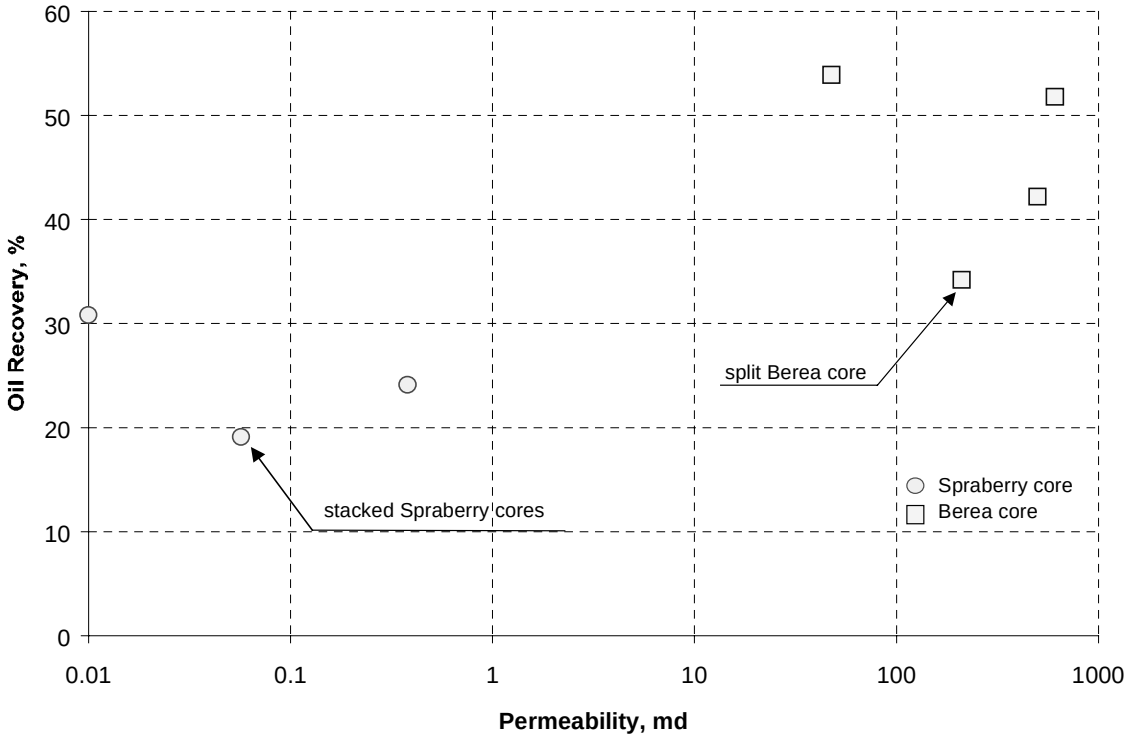

Fig. 10. Effect of rock permeability on CO_2 gravity drainage.

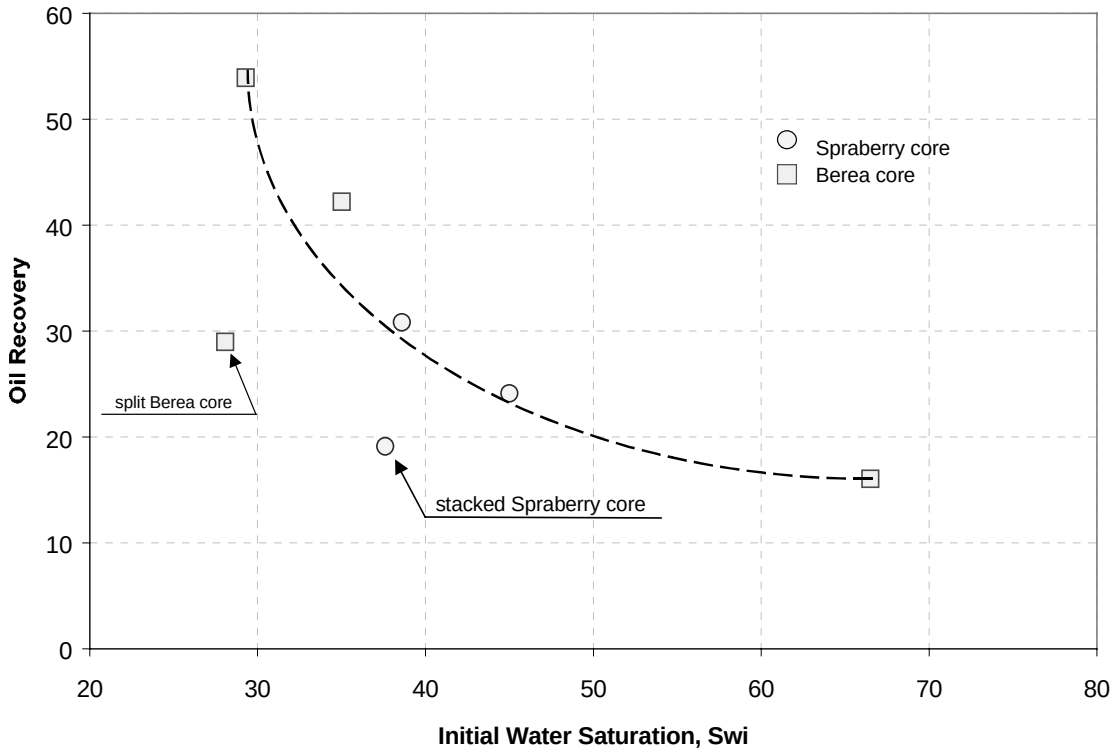

Fig. 11. Effect of initial water saturation on CO_2 gravity drainage.

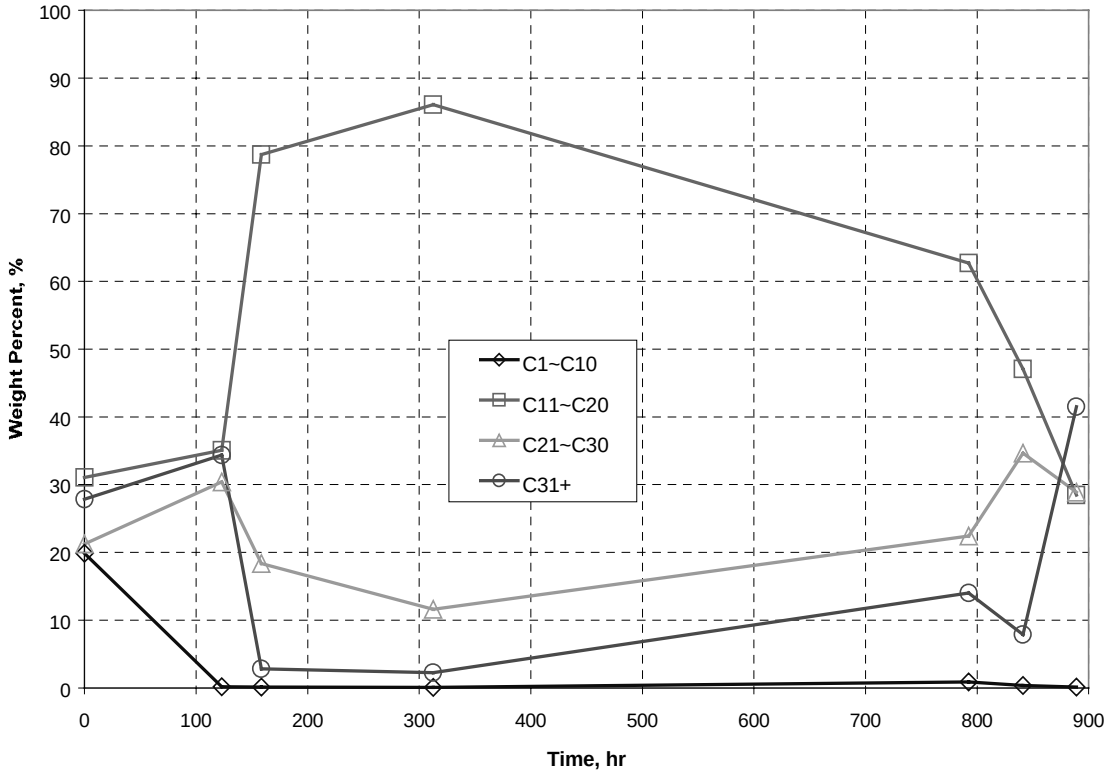

Fig. 12. Change of component distribution by weight with time.