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# *APPLICATIONS OF ADVANCED PETROLEUM PRODUCTION TECHNOLOGY AND WATER ALTERNATING GAS INJECTION FOR ENHANCED OIL RECOVERY - MATTOON OIL FIELD, ILLINOIS*

*COOPERATIVE AGREEMENT NUMBER DE - FC22 - 93BC14955*

*AMERICAN OIL RECOVERY, INC.*
*DECATUR, ILLINOIS*

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*Date of Report:* *April 30, 1994*

*Award Date:* *December 29, 1992*

*Anticipated Completion Date:* *March 31, 1994*

*Government Award for Current Year:* *$ 702,091.00*

*Program Manager:* *Michael R. Baroni*

*Principal Investigator:* *Michael R. Baroni*

*Technical Project Officer:* *Gene Pauling*

*Reporting Period:* *JANUARY - MARCH 1994*

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*THIS PROJECT HAS BEEN TERMINATED. PHASE II WILL NOT BE IMPLEMENTED. A FINAL TECHNICAL REPORT WILL BE SUBMITTED PRIOR TO THE END OF THE CALENDAR YEAR.*

*US/DOE patent clearance is not required prior to the publication of this report.*

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## OBJECTIVES

The objectives of this project are to continue reservoir characterization of the Cypress Sandstone; to identify and map facies-defined waterflood units (FDWS); and to design and implement water-alternating-gas (WAG) oil recovery utilizing carbon dioxide ($CO_2$). The producibility problems are permeability variation and poor sweep efficiency. Phase 1 of the project focuses on the development of computer-generated geological and reservoir simulation models that will be used to select sites for the demonstration and implementation of $CO_2$ displacement programs in Phase 2. Included in Phase 1 is the site selection and drilling of an infill well, coring of the Cypress interval, and injectivity testing to gather information used to update the reservoir simulation model. Phase 2 involves field implementation of WAG. Technology Transfer includes outreach activity such as seminars, workshops, and field trips.

## SUMMARY OF TECHNICAL PROGRESS

### Relative permeability curve at saturation pressure of 500 psig

Determination of experimental relative permeability curves using Cypress core plugs from AOR-Seaman No. 15 were continued during this report period. The same experimental procedures described in the fourth quarterly report for the determination of relative permeability curves at 1000 psig were followed. The Mattoon crude oil was, however, saturated with $CO_2$ at 500 psig instead of 1000 psig.

The following runs were conducted:

(a). Brine displacing $CO_2$-saturated Mattoon crude oil (Table 1; fig. 1)
(b). $CO_2$-saturated Mattoon crude oil displacing brine (Table 2; fig. 2)
(c). $CO_2$ displacing $CO_2$-saturated Mattoon crude oil (Table 3; fig. 3)
(d). $CO_2$-saturated Mattoon crude oil displacing $CO_2$ (Table 4; fig. 4).

Results are shown in Tables 1 to 4 and figures 1 to 4.

### Water/Cypress Rock Compatibility Tests

Two Cypress Sandstone core samples from the "E" interval of the No. 15 AOR-Seaman well were tested for compatibility with Mattoon city water. Mattoon city water was under consideration as supply for the water-alternating-gas (WAG) injection program in the Sawyer unit.

The tests were performed in a Hassler-type core holder at an injection rate of 1 cc/min with a back pressure of 100 psi and a confining pressure of 1,000 psi. In the first test, water containing 2% sodium chloride (NaCl) was injected; this was followed by the city water. The initial 2% NaCl brine injected into the core represented the saline aqueous environment existing in Cypress reservoirs. A minimum of 20 pore volumes of each water sample was injected before changeover and the

permeability of the core plug to each water sample was also measured (Table 5). The result shows that the core sample permeability decreased by 6.5% by Mattoon city water. Subsequently, brine containing 2% potassium chloride (KCl) was injected to stabilize fresh water sensitive clays in the core sample. During this time, permeability reduction stopped; however, it resumed when city water was reinjected. Permeability reduction continued because the first injection of fresh water may have already affected water-sensitive clays and dislodged clay particles which migrated and caused permeability reduction. Altogether, 11.1% reduction in permeability occurred by the end of the experiment due to the use of Mattoon city water.

The protocols for the second and third tests included injection of brine containing 2% KCl prior to the injection of the Mattoon city water. The purpose of these tests is to investigate whether the injection of brine containing 2% KCl, acting as a clay stabilizing agent, would prevent permeabilty reduction. The results show that, within the limits of experimental error, permeability reduction did not occur (Tables 6 and 7). These experiments show that clays within the Cypress Sandstone at Mattoon field are fresh water sensitive and will be affected if contacted with fresh water such as the city water. However, injection of a clay stabilizing agent prior to fresh water injection, may prevent permeability reduction caused by clay swelling, dislodgement and migration.

**Reservoir simulation of Sawyer unit**

The reservoir simulation model of the Sawyer unit, previously developed, was updated with production and pressure data during the reporting period. Figure 5 shows the historical and predicted oil production from the Sawyer unit. The predicted cumulative oil production increases with the number of producing wells. For instance, up to 40,000 additional barrels of oil can be recovered in four years with the recompletion of five more oil producing wells (No.13-W Brining, No. 1 V. Strohl, No. 1 M. Sawyer community 1, No. 1 Sawyer community 1, No. 2 Sawyer community 1 ) in the E-interval ( Figure 6).

**Field Testing**

**Sawyer unit**

Natural gas produced from the new infill well AOR-Seaman #15 was sampled on March 11, 1994 and analyzed in the ISGS laboratory. The produced gas contained 13.22% carbon dioxide (Table 8). Since the original solution gas in Mattoon crude oil contained less than 1% carbon dioxide, the result indicated that the injected carbon dioxide from No. 1 Sawyer Community No. 3 has arrived at Seaman No. 15. Oil production from AOR-Seaman #15 during the reporting period averaged 4.3 BOPD.

## Pinnell unit

*Cyclic $CO_2$ injection in Pinnell Uphoff No.14*

One hundred eighty four (184) tons of $CO_2$ were injected into Pinnell Uphoff No. 14 from Dec. 20 to Dec 21, 1993. After a soak period of 12 days, the well head pressure decreased from the post-injection pressure of 600 to 325 psig. Average oil production rate between January 3, 1994 to February 28 1994 was 4.0 BOPD.

*Pressure Testing of Pinnell unit*

Two thousands tons of liquid $CO_2$ were injected into 3-W Pinnell in December 1993 in order to verify the existence of a permeability barrier between the injector 3-W Pinnell and the producer No. 1 Pinnell-Uphoff. Pressure response observed in No. 1 Pinnell-Uphoff was minimal during the injection period. However, oil production increased from the pre-injection rate of 1 BPOD to an average of 4.3 BOPD during January but have since decreased to below 3 BOPD. This result shows that there may be favorable oil production response from No. 1 Pinnell-Uphoff if water is injected into 3-W Pinnell (A-interval).

**Technology transfer**

Technology transfer activities during the reporting period included:

1. *Presentation at the Illinois Oil and Gas Association Annual Meeting, Evansville, Indiana*

A talk entitled " Enhanced Recovery Opportunities in Illinois Basin Using Carbon Dioxide" was presented at the IOGA Annual Meeting (March 2 - 4, 1994). The history of the progress of this demonstration project, problems encountered, lessons learned, and advantages of $CO_2$ applications were discussed.

The presentation also provided opportunities for one-to-one consultations with several independent oil operators.

2. *An abstract and pre-print accepted for presentation at CPS of CIM*

A paper titled "Laboratory experiments and reservoir simulation studies in support of a $CO_2$ injection project in Mattoon Field, Illinois, USA" was accepted for presentation at the 45th annual technical meeting of the Canadian Petroleum Society of CIM in Calgary, June 12-15 1994. The abstract accompanying the pre-print is reproduced below:

This paper describes the results of rock and fluid property measurements and the results of integrated reservoir modeling associated with Phase I of a demonstration of $CO_2$-assisted oil recovery in the Cypress Sandstone reservoirs at Mattoon Field, Illinois. The objectives of the project are to characterize the Cypress Sandstone through an integrated geologic and engineering approach; to identify facies-defined waterflood units: to design and implement an enhanced oil recovery program utilizing $CO_2$; and to transfer technology to oil and gas operators.

Although results from slim-tube displacement experiments show that implementation of a miscible flood may not be possible, phase behavior experiments show that the effects of dissolved $CO_2$ on oil swelling and viscosity reduction are significant even at pressures below miscible conditions. Results from core flood tests indicate that oil recovery from immiscible displacement of reservoir crude oil with carbon dioxide will increase with displacement pressure.

Reservoir simulation studies and injectivity tests on the Pinnell Unit of the project area indicate poor inter-well communication and limited areal extent of the producing interval of this unit. Inefficient displacement of reservoir crude by the injected $CO_2$ is also indicated from production tests.

Injectivity tests on the Sawyer Unit of the project area show good inter-well communication. Results from analyses of core samples from a newly drilled infill well within this unit confirm the isolation of the target E-sandstone interval from the extensively waterflooded lower B and C sandstone intervals. Reservoir simulation results indicate that a significant amount of additional oil can be recovered by the implementation of a water alternating gas (WAG) injection program utilizing eight or more oil producers.

Table 1: Relative Permeability
(Brine displacing $CO_2$ saturated Mattoon oil at 500 psig)

| | Experimental Data | Data | Regressed Data | Data |
|---|---|---|---|---|
| water saturation (Sw) swi=37.34 | Kro | Krw | Kro | Krw |
| 37.34 | 0.2560 | 0.0000 | 0.2560 | 0.0000 |
| 40.00 | | | 0.2143 | 0.0041 |
| 45.00 | | | 0.1430 | 0.0163 |
| 50.00 | | | 0.0821 | 0.0314 |
| 52.84 | 0.0475 | 0.0379 | 0.0528 | 0.0409 |
| 54.58 | 0.0388 | 0.0407 | 0.0371 | 0.0469 |
| 58.00 | 0.0128 | 0.0511 | 0.0124 | 0.0594 |
| 61.16 | 0.0000 | 0.0720 | 0.0000 | 0.0714 |

Table 2: Relative Permeability
($CO_2$ saturated Mattoon oil displacing brine at 500 psig )

| | Experimental Data | Data | Regressed Data | Data |
|---|---|---|---|---|
| oil saturation (So) | Krw | Kro | Krw | Kro |
| 38.84 | 0.0719 | 0.0000 | 0.0719 | 0.0000 |
| 45.00 | | | 0.0448 | 0.0000 |
| 50.00 | | | 0.0267 | 0.0002 |
| 55.00 | | | 0.0120 | 0.0066 |
| 57.00 | | | 0.0074 | 0.0201 |
| 59.00 | | | 0.0035 | 0.0544 |
| 60.00 | | | 0.0020 | 0.0861 |
| 61.13 | 0.0040 | 0.1480 | 0.0006 | 0.1411 |
| 61.30 | 0.0035 | 0.1780 | 0.0005 | 0.1519 |
| 62.66 | 0.0000 | 0.2150 | 0.0000 | 0.2150 |

Table 3: Relative Permeability
($CO_2$ displacing $CO_2$ saturated Mattoon oil at 500 psig )

| | Experimental Data | Data | Regressed Data | Data |
|---|---|---|---|---|
| gas saturation (Sg) | Kro | Krg | Kro | Krg |
| 37.34 | 0.2682 | 0.0000 | 0.2682 | 0.0000 |
| 39.06 | 0.2065 | 0.0016 | 0.2268 | 0.0032 |
| 39.87 | 0.1916 | 0.0020 | 0.2090 | 0.0039 |
| 42.58 | 0.1494 | 0.0036 | 0.1550 | 0.0055 |
| 45.06 | 0.1160 | 0.0054 | 0.1138 | 0.0067 |
| 47.00 | 0.0922 | 0.0069 | 0.0868 | 0.0075 |
| 52.00 | | | 0.0362 | 0.0093 |
| 55.00 | | | 0.0176 | 0.0102 |
| 60.00 | | | 0.0023 | 0.0115 |
| 61.40 | 0.0000 | 0.0125 | 0.0000 | 0.0125 |

Table 4: Relative Permeability
($CO_2$ saturated Mattoon oil displacing $CO_2$ at 500 psig )

| | Experimental Data | Data | Regressed Data | Data |
|---|---|---|---|---|
| liquid saturation (Sw & So) | Krg | Kro | Krg | Kro |
| 77.20 | 0.0730 | 0.0000 | 0.0730 | 0.0000 |
| 83.60 | | | 0.0591 | 0.0119 |
| 88.60 | | | 0.0260 | 0.0673 |
| 92.95 | 0.0134 | 0.1395 | 0.0108 | 0.1501 |
| 92.63 | 0.0001 | 0.1656 | 0.0091 | 0.1668 |
| 93.94 | 0.0000 | 0.3041 | 0.0000 | 0.3041 |

Table 5: Compatibility testing of Sample MA 1752.4 - No. 15 AOR-Seaman well Cypress Sandstone, Mattoon field, Coles County, Illinois

ID: MA1752.4
Length = 4.838 cm Porosity = 18.5%
Diameter = 2.540 cm

| Fluid Injected | Permeability, md |
|---|---|
| Air | 60.7 |
| 2% NaCl | 36.8 |
| **City water** | **34.4** |
| 2% KCl | 34.8 |
| **City Water** | **32.7** |

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Table 6: Compatibility testing of Sample MA 1754 - No. 15 AOR-Seaman well Cypress Sandstone, Mattoon field, Coles County, Illinois

ID: MA1754
Length = 4.464 cm Porosity = 18.5%
Diameter = 2.540 cm

| Fluid Injected | Permeability, md |
|---|---|
| Air | 34.4 |
| 2% KCl | 22.5 |
| **City water** | **22.5** |

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Table 7: Compatibility testing of Sample MA 1751.7 - No. 15 AOR-Seaman well Cypress Sandstone, Mattoon field, Coles County, Illinois

ID: MA1751.7
Length = 5.204 cm Porosity = 16.7%
Diameter = 2.540 cm

| Fluid Injected | Permeability, md |
|---|---|
| Air | 36.8 |
| 2% NaCl | 22.9 |
| 2% KCl | 22.2 |
| **City Water** | **22.5** |

Table 8: REPORT OF GAS ANALYSIS

LAB #: 5089 REQUEST #: 21416
SAMPLED: 3/11/94 ANALYZED: 3/18/94 REPORTED: 3/18/94
COUNTY: COLES
LOCATION: 35-12 -07
WELL NAME: Amer.Oil Recovery J.H.Seaman #15
GAS SAMPLE CONTAINER: Cylinder
FORMATION: Cypress
PRODUCTING ZONE DEPTHS:
GAS FLOW RATE:

RESULTS OF ANALYSIS
in volume percent, normalized

| | |
|---|---|
| CARBON DIOXIDE ($CO_2$)----- | 13.22 |
| OXYGEN/ARGON ($O_2$ + Ar)--- | 0.19 |
| NITROGEN ($N_2$)---------- | 3.79 |
| METHANE ($CH_4$)---------- | 30.40 |
| ETHANE ($C_2H_6$)---------- | 10.08 |
| PROPANE ($C_3H_8$)---------- | 23.94 |
| ISO-BUTANE (I-$C_4H_{10}$)----- | 2.81 |
| N-BUTANE (N-$C_4H_{10}$)------- | 9.91 |
| ISO-PENTANE (I-$C_5H_{12}$)---- | ND |
| N-PENTANE (N-$C_5H_{12}$)------ | 0.01 |
| HEXANES + ---------- | 5.66 |

BTU/CU.FT. DRY @
60°F & 14.7 PSIA:
TOTAL ----- 1794

SPECIFIC GRAVITY:
CALCULATED - 1.30

METHOD OF ANALYSIS: GAS CHROMATOGRAPHY ND = NOT DETECTED

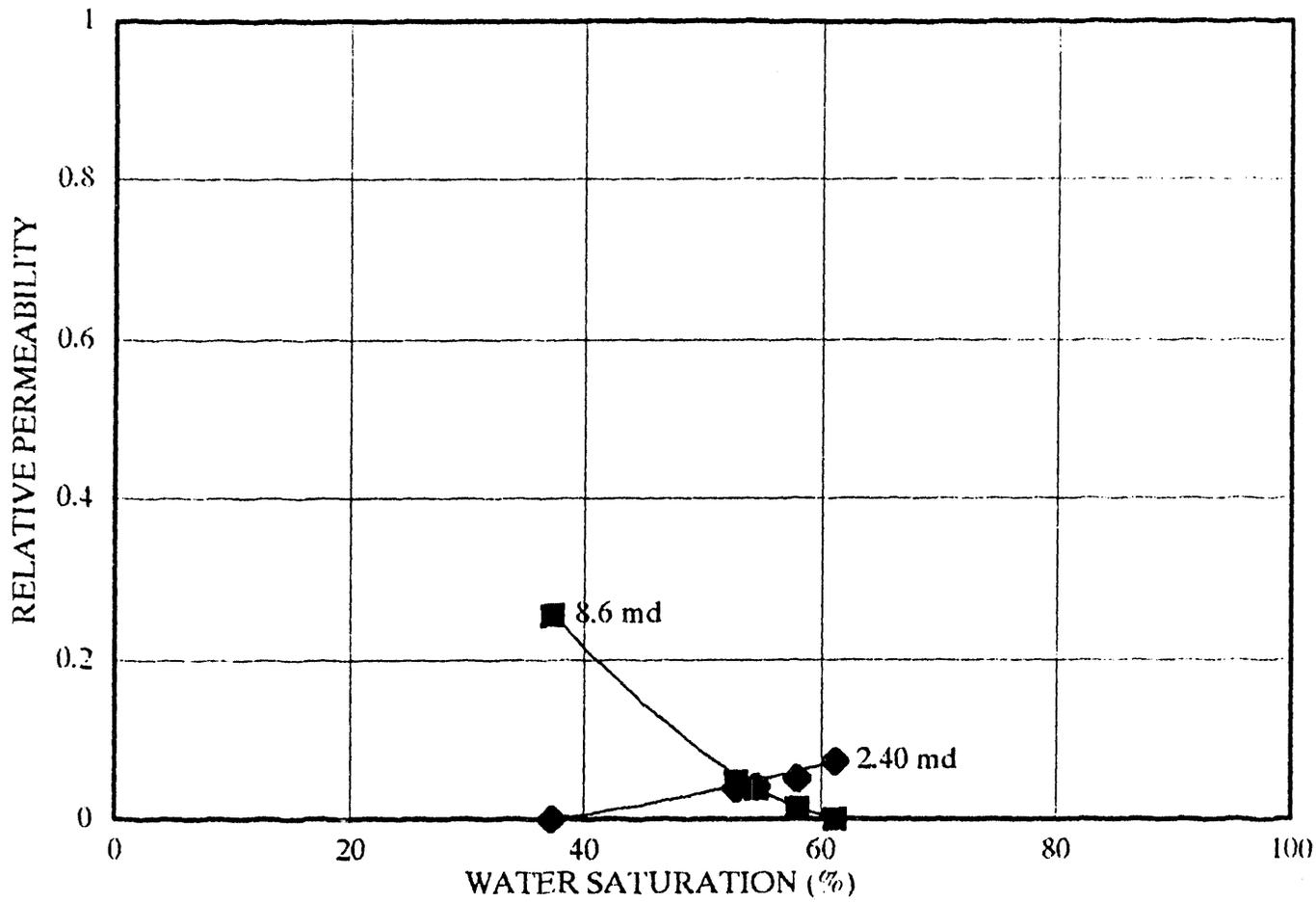


Fig. 1 - Brine displacing $CO_2$-saturation oil at 500 psig using Mattoon Cypress Sandstone core plug

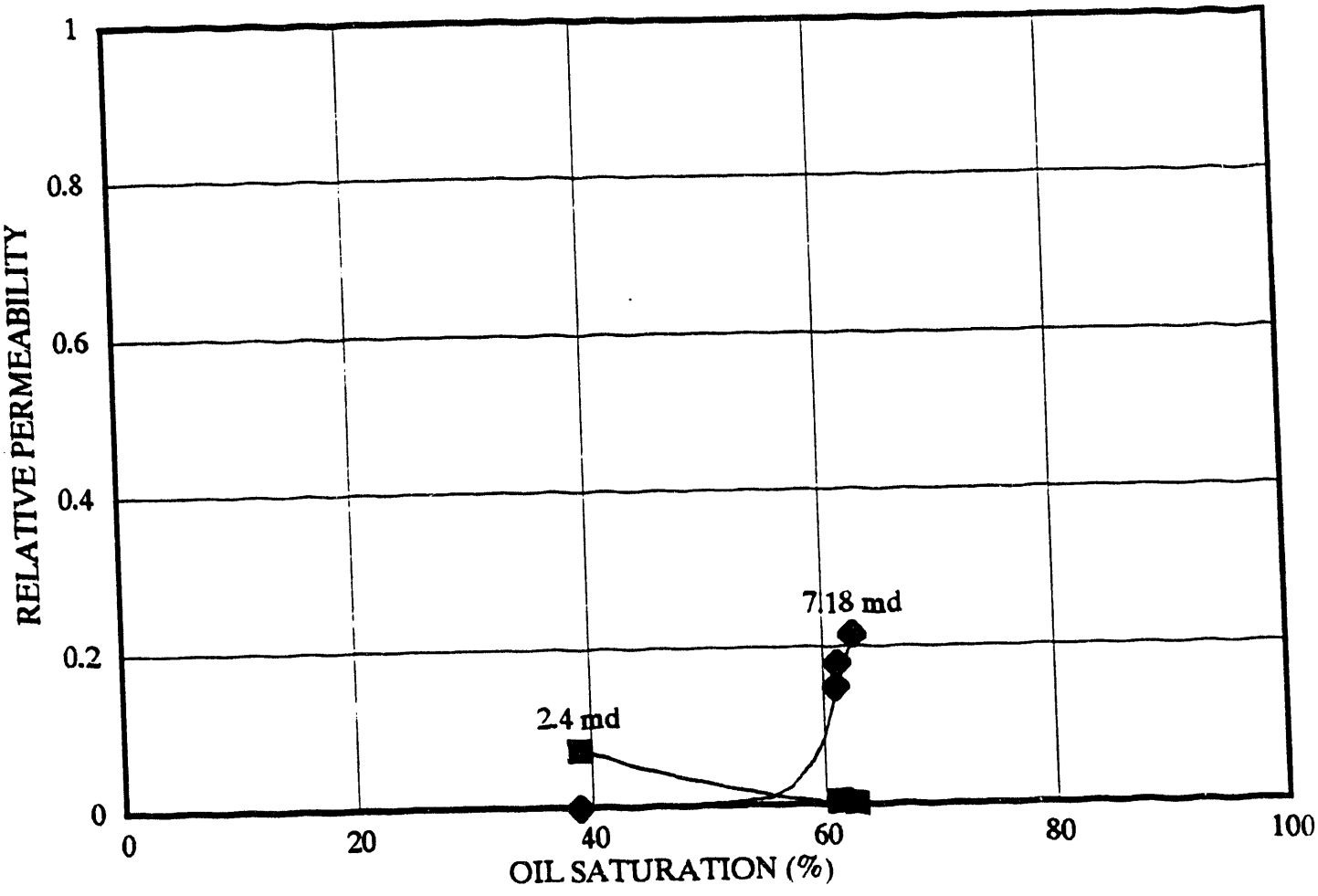


Fig. 2 - CO2 -saturated oil displacing brine at 500 psig using Mattoon Cypress Sandstone core plug.

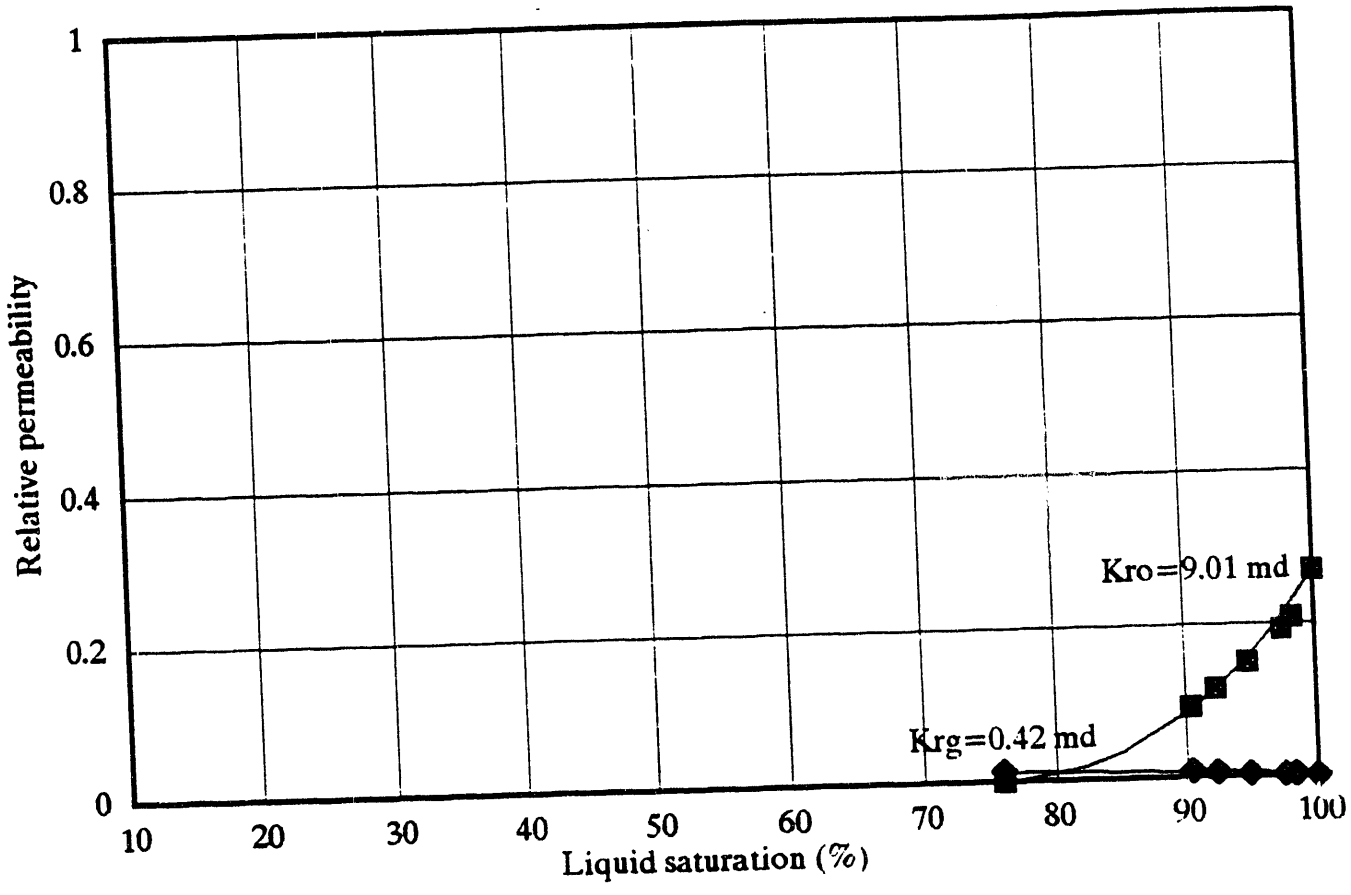


Fig. 3 - CO2 displacing saturated oil at 500 psig using Mattoon Cypress Sandstone core plug.

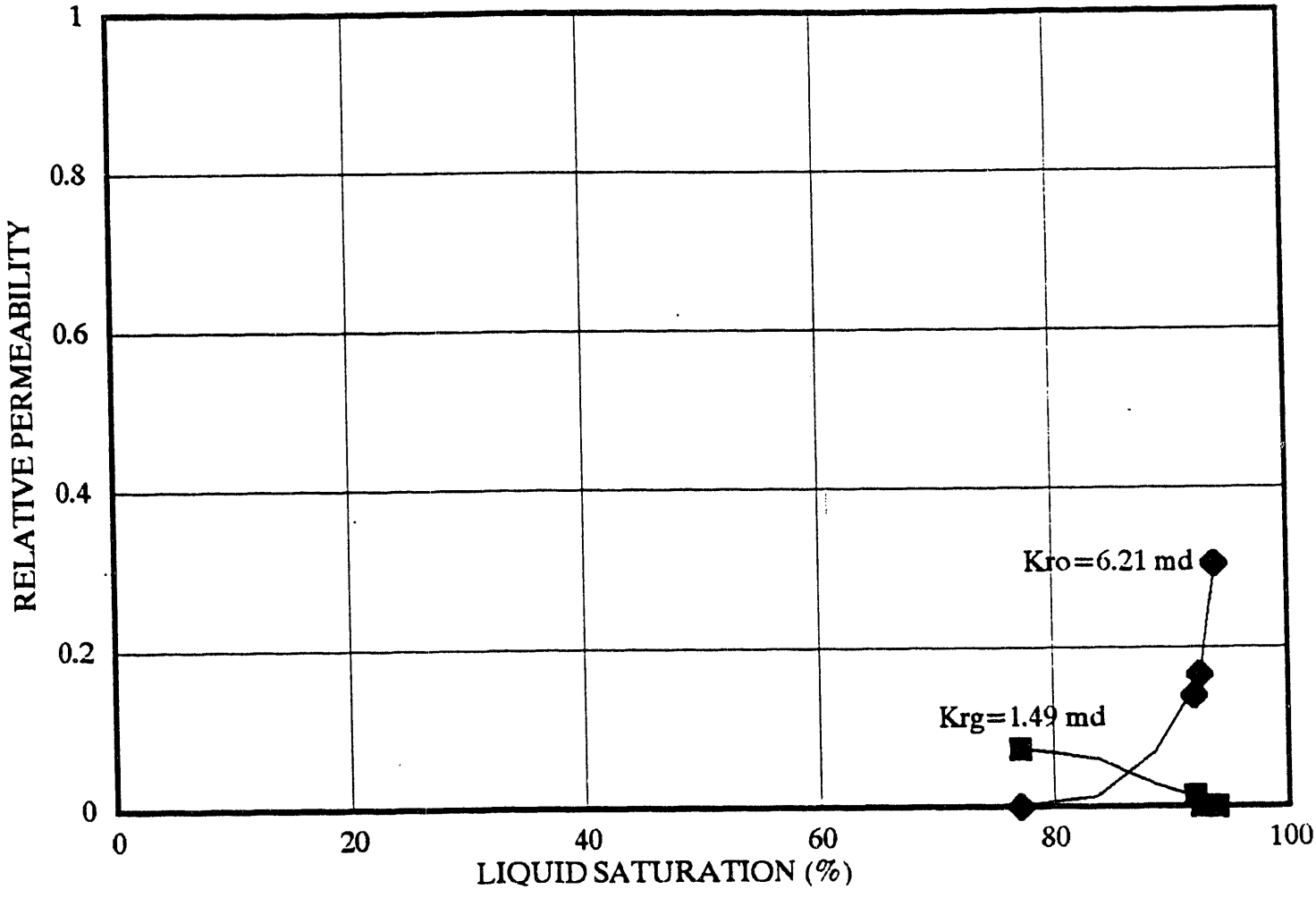


Fig. 4 - Saturated oil displacing CO2 at 500 psig using Mattoon Cypress Sandstone core plug.

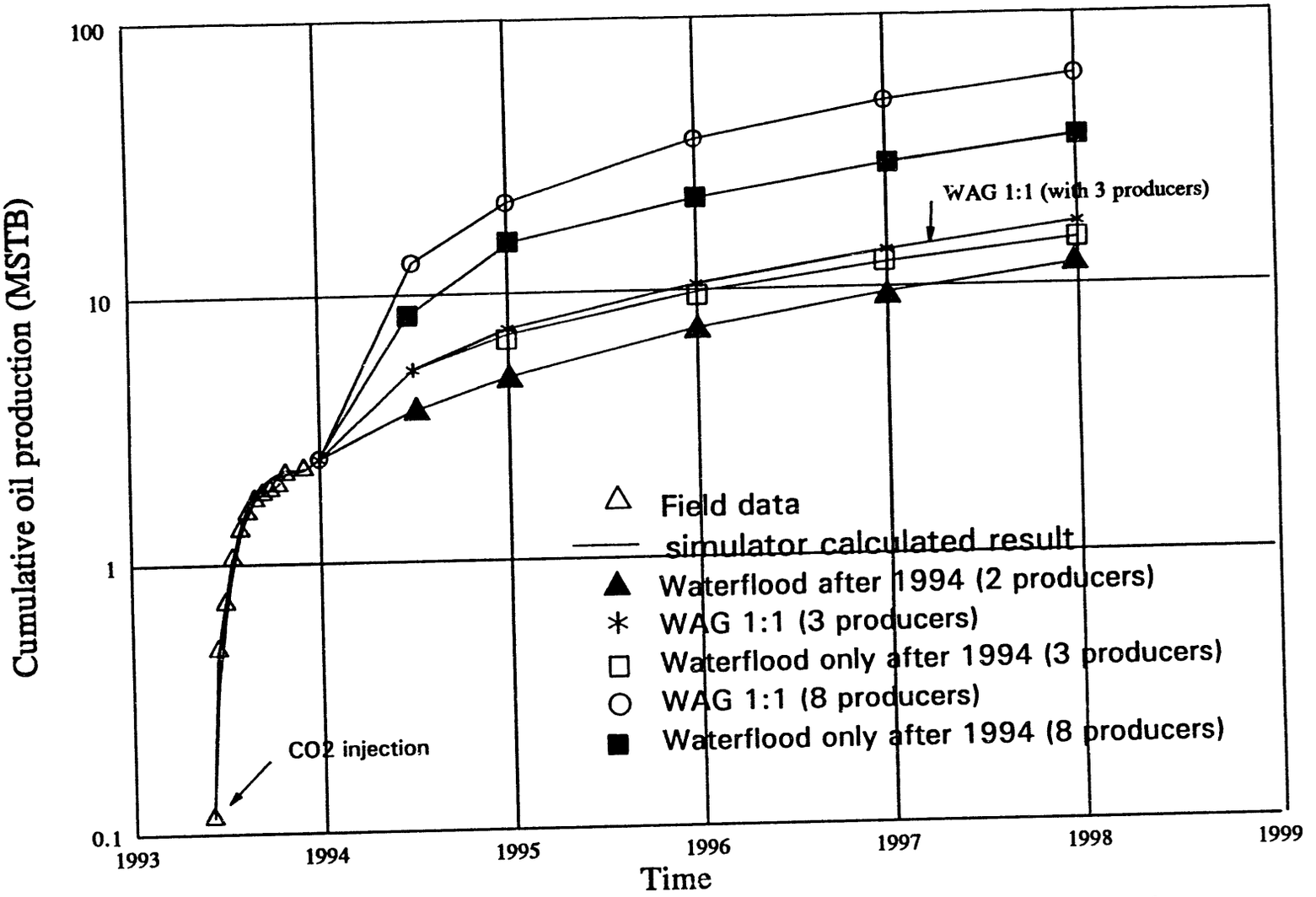


Fig. 5 - Historical and projected oil production of Sawyer unit

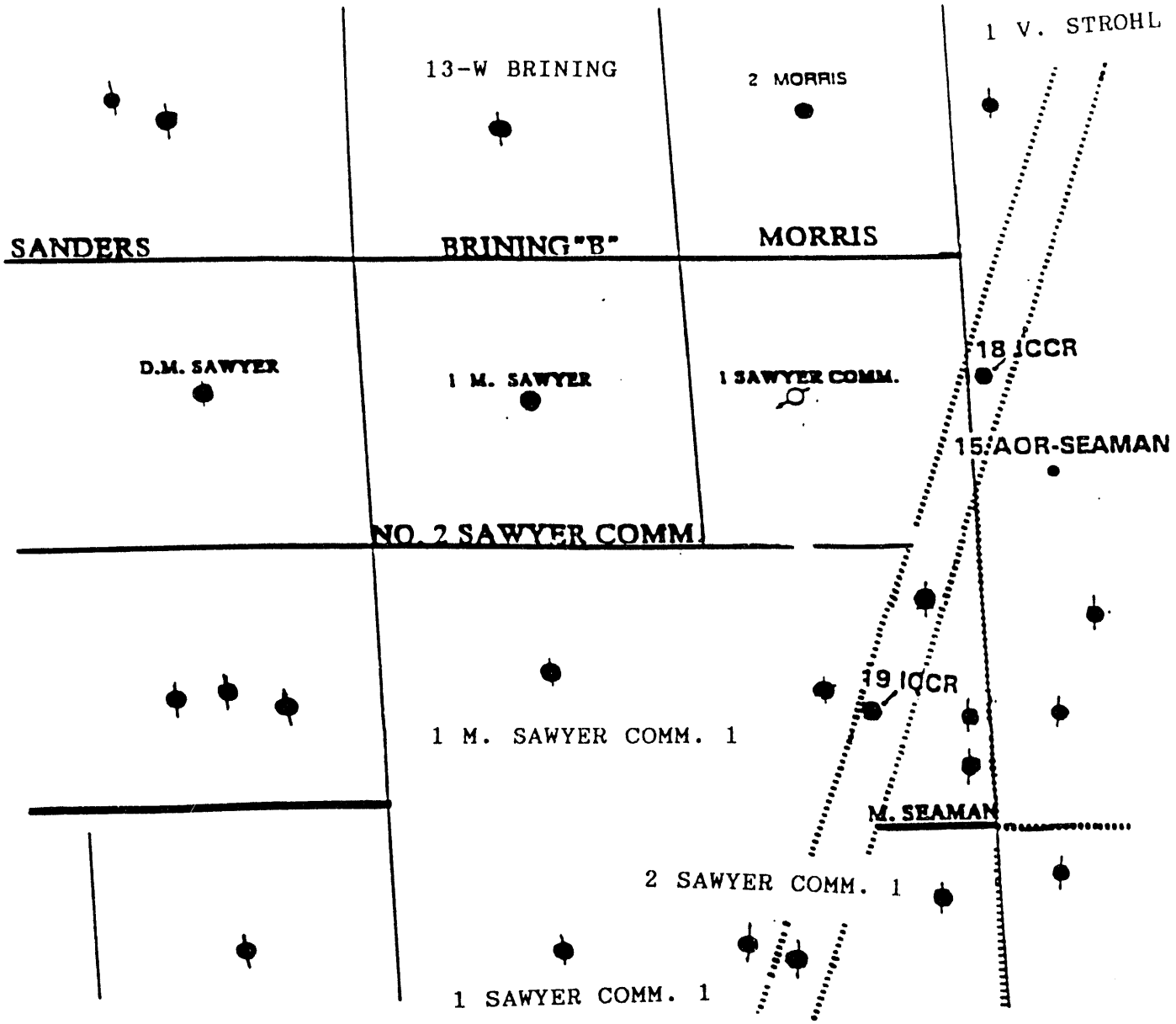


Fig. 6 - Location Map of Sawyer CO2 Injection Unit

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7/19/94

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