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AN EVALUATION OF THE CO₂ PILOT
MALJAMAR FIELD
LEA COUNTY, NEW MEXICO

By
Leslie B. Plumb
Howard H. Ferrell

February 1989

Performed Under Contract No. AC19-85BC10830

K&A Energy Consultants, Inc.
Tulsa, Oklahoma

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Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

E.B. Nuckols, Project Manager
Bartlesville Project Office
P.O. Box 1398
Bartlesville, OK 74005

Prepared by
K&A Energy Consultants, Inc.
6849 East 13th Street
Tulsa, OK 74112

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AN EVALUATION OF THE CO₂ PILOT
MALJAMAR FIELD,
LEA COUNTY, NEW MEXICO

SUMMARY

This report reviews the performance of the miscible CO₂ pilot in the Maljamar Field, Lea County, New Mexico. The project was conducted by Conoco under the Tertiary Incentive Crude Oil Program. The project was initiated in 1981 and completed January 1, 1986. The project involved CO₂ floods in two separate reservoirs conducted simultaneously using dually completed wells in a 5-acre inverted 5-spot pattern. Control of fluid movement in the pilot was achieved by utilizing four confining injection wells outside the pattern, as well as two observation wells inside the pattern.

The purpose of the pilot was to provide data for computer modelling of the reservoir and for facilities design and economic analysis of a full scale project. Conoco accomplished this purpose and has begun fieldwide expansion of CO₂ flooding in both Maljamar reservoirs based on the results of this pilot.

The Maljamar pilot demonstrated that CO₂ reduced oil saturation below waterflood residual in both reservoirs. Interpretation of the pilot results was enhanced by using interpattern logging monitor wells completed with fiberglass pipe and utilizing four outside wells for water injection to contain the CO₂ within the pilot area. Valuable operating experience in handling corrosion problems was also gained during the pilot operation.

INTRODUCTION

Conoco is operator of the 8040-acre Maljamar Cooperative Agreement (MCA) Unit which comprises approximately 20 percent of the Maljamar Field. Figures 1 and 2 show the location of the MCA Unit and the pilot area location within the unit.

The Maljamar Field was discovered in 1926, but the majority of the wells were drilled in the 1940's. Production is from the Upper Permian Grayburg and San Andres formations with producing depths between 3600 feet and 4200 feet. Figure 3 is a type log of the Grayburg-San Andres section in the MCA Unit. The San Andres formation is a dolomite, while the shallower Grayburg formation is a dolomitized sand. Both formations produce from stratigraphic traps over a wide area of the Permian Basin. The Maljamar Field is defined by porosity and permeability pinchouts on the north and west sides and has a downdip water contact on the south and east sides. The primary production mechanism in both reservoirs was solution gas drive with no significant evidence of water encroachment.¹ The initial reservoir pressure is not known but is estimated at 1300 to 1350 psi. Tables 1 and 2 give a tabulation of reservoir thickness, porosity, and permeability of the three main layers in the Grayburg 6th zone and San Andres 9th massive zone reservoirs listed by layer and quadrant.

There have been several efforts at production enhancement over the life of the field:

- 1) Reinjection of produced gas was begun in 1942 which resulted in some incremental increase in production.
- 2) Waterflooding was begun in 1963 in several operating units and was expanded to cover the entire field in 1965 to 1969. The reservoir pressure at the start of the waterflood was approximately 600 psi.
- 3) An infill drilling program designed to accelerate the waterflood and improve ultimate recovery was implemented from 1971 to 1973. This development resulted in the waterflood being operated with 80-acre inverted 9-spot patterns.

The cumulative oil recovery from the MCA Unit up to the start of the waterflood was 38.7 MMB (72 B/AF). An extrapolation of waterflood performance indicates an incremental production gain by waterflood of 63 MMB (117 B/AF) or 23 percent of OOIP.¹ The estimated total cumulative production by primary plus gas injection plus waterflood is 119.4 MMB (222 B/AF) or 44 percent of OOIP. Thus, a remaining oil content of about 60 percent of OOIP (302 B/AF) represented a very suitable target for an EOR project.

EOR FEASIBILITY STUDY

CO₂ flooding was the only technically feasible EOR process for Maljamar because of the high gravity crude, low permeability matrix and the very high water salinity. A very significant advantage for CO₂ is that the minimum miscibility pressure was determined (from slim tube floods) to be 1515 psi, compared to the reservoir pressure after waterflooding of approximately 2500 psi.¹

In order to control the economic risks for a large scale CO₂ flood, it was decided in 1978 to develop a pilot CO₂ flood in the MCA Unit. The questions to be answered by the pilot included:

- 1) Can CO₂ mobilize the oil in the reservoir in order to build an oil bank?
- 2) What will be the residual oil saturation in the reservoir following the passage of the CO₂ front?
- 3) How much CO₂ will be required for an effective flood?
- 4) What injection rates can be achieved with CO₂? What rates will be required?

These questions would be resolved by a dually completed 5-acre pilot in both the Grayburg and San Andres formations. Final design of a field scale project would stem from reservoir simulations and design evaluation of the pilot data. The pilot was sized to a 5-acre pattern to meet the requirement for a timely evaluation, and an inverted 5-spot pattern was selected to minimize the quantity of CO₂ required.¹

PILOT DEVELOPMENT

The pilot pattern is shown in Figure 2. The CO₂ injection well (358) was drilled in the center of a 20-acre tract to utilize four existing producing wells, 48, 66, 256, 262, which were converted for water injection to provide backup pressure for the CO₂ injector.

Four new producers, 359, 360, 361, and 362, were drilled around injection Well 358 and inside the 20-acre pattern as shown in Figure 2. Well 358 was pressure-cored through both target zones to obtain reservoir oil and water saturation data and to provide core samples for additional lab work.

Pressure transient tests were conducted to determine reservoir continuity within the 20-acre area and to establish values for reservoir flow capacity. The tests involved a series of tests with extensive instrumentation in Well 358 and existing Wells 48, 66, 256, and 262.²

After establishing continuity, the pilot producer wells were drilled, cored, and logged. Reservoir fluid samples were obtained by means of the repeat formation tester. Phase behavior of the CO₂ and crude oil mixtures was developed by computer simulation based on PVT analysis of the reservoir fluids together, with slim tube flood tests.³

Additional pressure transient tests and well-to-well pulse interference tests were conducted between Well 358 (both zones) and Wells 359, 360, 361, and 362, to confirm the reservoir characteristics in the 5-acre pilot area.

These tests confirmed and augmented the data from the first set of tests on the 20-acre area. Reservoir capacity (kh) and capacity distribution for the simulator were derived from cores and pressure transient data.² Step rate-injection tests were conducted on Well 358 to determine maximum safe injection pressure which was less than the reservoir parting pressure.

Finally, two monitor wells, 363 and 364, were drilled on a straight line between injection Well 358 and producer Well 359 (Figure 2). These wells were cemented with fiberglass casing over the bottom 600 feet of the well to permit repeated electric logging through both productive zones to monitor oil bank build-up and movement through the reservoir by observing changes in reservoir fluid saturations.

Radioactive tracers (Cobalt-60 into the 6th zone and Cobalt-58 into the 9th zone) were injected into each producing zone, and these tracers were monitored by repeated runs using a total gamma scintillation counter type of sonde in the monitor wells, 363 and 364. Thus, logging monitoring wells were used both to observe which strata conducted injected fluids and how much the saturations changed in the conducting strata. This information was valuable for reservoir simulation.²

There were several unique features to this pilot:

- 1) The two interior observation wells were cased with fiberglass pipe to permit use of electric logs for measuring reservoir saturations and tracking the advance of the flood front which was critical to permitting effective computer simulation of the process.
- 2) The injection of brine into the four wells outside the pattern provided backup for the center pilot well injection to minimize injection cost and prevent the loss of the drive energy.

- 3) Dual completions of the wells in the two reservoirs allowed simultaneous use of well bores and equipment. However, operational problems, particularly corrosion, were aggravated by dually completed producing wells. Consequently, dual producers were not recommended for full scale operation although the dually completed injectors appeared to pose no real problems.

OPERATING PLAN

The time schedule of the pilot operating plan is shown in Figure 4. Initially, fresh water was injected in Well 358 in order to establish that both zones were watered out, based upon responses in the producing wells. Further, fresh water was injected to provide a baseline profile for E-log runs in the two monitor wells, 363 and 364.⁴ Comparison logs run during subsequent brine injection indicated the vertical intervals being swept, since oil saturations remained the same and the observed resistivity differences reflected the salinities of the two injected fluids. Brine was continuously injected in the four backup injection wells outside the pattern during all phases.

Following brine injection in phase two, different radioactive tracers were injected into each of the two reservoirs through the center injector. These tracers were detected by a gamma-ray sonde in the two monitor wells and indicated excellent vertical conformance of injection into both zones.⁴ Different tracers were injected into each of the four outside injectors, 48, 66, 256, and 262, so that their influence on each of the producer wells could be monitored through analysis of produced water.

CO₂ injection was not commenced until evidence of radioactive tracers were detected at the monitor wells in order to permit possible adjustments in the size of the CO₂ slug. However, no adjustments were thought to be necessary. After the start of CO₂ injection, the logging program was changed from gamma-ray logs to a combination induction electric/gamma ray/compensation neutron logs (IES/GR/CNL). The IES log indicated changes in water saturation, and the GR indicated presence of radioactive tracers. The CNL which responds to the presence of hydrogen ions indicated the presence of CO₂

by measuring the decrease in hydrogen ion density. By determining S_w and CO_2 saturations, oil saturation was obtained by difference, since there was no free gas saturation. Thus, an oil bank was detected as it moved past the monitor wells.⁴

Injection rates of CO_2 and brine were controlled into both zones. Production from each zone in each of the four producer wells was also controlled in an attempt to balance the flood front advance.¹

OPERATING PROBLEMS

Corrosion was a troublesome operating problem. It is estimated that during the pilot operation, corrosion was 10 times more severe than had been experienced in the MCA waterflood.¹ The corrosion was complicated by three factors:

- 1) Producing water cuts were near 100 percent at the start and remained above 80 percent throughout the pilot life.
- 2) Dually completed producers made inhibition treatments much more difficult and probably less effective. Therefore, it was recommended that dual completions be avoided if possible.
- 3) High fluid levels in producing wells were maintained to control reservoir pressure and balance the flood front advance.

Although no specific data was presented on the cost of the corrosion problem, it is believed the expansion must optimize corrosion inhibition by the advanced techniques embodied in the later pilot in order to limit operating costs to acceptable levels.

Only minor problems involving oil or grease in very small amounts which were left in pumps, valves, metering devices, etc., were encountered with the CO_2 injection, and these were handled simply by a very thorough cleaning of these pieces of equipment.¹

DATA COLLECTION

Accurate and consistent data needed for material balance of CO₂ volumes required computerized mass flow meters, temperature sensors, gas gravimeters, and infra-red based CO₂ analyzers for produced gas containing CO₂. The instrumentation system gave dependable data at a reasonable cost.

Produced liquids were sampled and analyzed frequently for composition and tracers. Bottom-hole pressures and temperatures were calculated from surface data but were verified periodically by downhole surveys to insure accurate calculation of the reservoir volume of CO₂ injected. Unfortunately, the accuracy of well test data on producing wells was affected by the corrosion inhibition treatment which required circulation of fluids in the wells. If the well produced only a small volume of oil, the test results were suspect.

Computerized data storage and retrieval was added partway through the life of the pilot. This system was valuable in making data readily available in useable form for the evaluation and simulation programs.¹

Logging data was collected from the two monitored wells between August 1981 and May 1984. There were 34 runs in MCA 363, nearest the injector well, and 17 runs in MCA 364. The changes in reservoir fluid saturations were correlated with the injection volume in the four separate injection phases. In addition, frequent gamma-ray logging runs were made to detect the radioactive tracers.⁴

PATTERN BALANCING

An attempt was made to balance the injection and production in each zone in order to obtain approximately equal response in both zones in all four quadrants and to obtain a good horizontal sweep efficiency in each zone. Injection rates were controlled with manual control valves at first, but later microprocessor controlled valves were installed to optimize the labor-time requirements. Control valves gave dependable and precise control over the injection.¹

Attempts to control the bottom-hole pressure in producers by regulating producing rates required much attention at a considerably high labor cost. Operating the wells on time clocks was satisfactory in the early life of the pilot, but after CO₂ production began at the producers, some of the wells continued to flow when the pumping units were shut down, requiring installation of chokes in these wells. Other producing wells pumped off and were unable to produce at the desired rates. These wells probably experienced some plugging by scale, corrosion, asphaltenes precipitated from the oil or from formation fines resulting from the effects of the CO₂. Further credence of plugging is given by the decline in injectivity during the life of the pilot (Figures 6 and 8).

Since production performance of the individual producing wells was not reported, it was not clear whether the response was similar in each zone of each producer. At any rate, Conoco was able to adequately simulate the pilot response.³

EVALUATION OF PERFORMANCE

Table 3 shows the fluid characteristics of the two zones flooded in this pilot operation. Injection and production histories of the two reservoirs are shown graphically in Figures 5 through 8. It is clearly evident that an oil bank was built and that significant oil recovery resulted from the CO₂ injection in both reservoirs. The oil rate and cumulative production for the two formations was nearly equal; however, the CO₂ produced from the Grayburg was noticeably higher. Figures 9 through 12 present the observed compared to the simulator results of cumulative oil produced (percent of original oil in place) and cumulative produced CO₂ (percent of CO₂ injected). The observed and simulated saturation of CO₂ and oil versus time are given for the middle layer in the Grayburg and San Andres in Figures 13 and 14.

The Grayburg 6th zone recovered an additional 11 percent of original oil-in-place as a result of the CO₂ injection while the San Andres 9th massive zone only recovered an additional 4 percent. It is also seen that the Grayburg zone produced approximately 23 percent of the CO₂ injected while the San Andres zone produced approximately 9 percent of the CO₂ injected.

The apparent better performance of the Grayburg can probably be explained by a design error in the pore volume of the San Andres zone (Table 4). The actual pore volume was probably significantly greater than estimated in the pilot design; therefore the CO₂ slug was too small. Other possible explanations for the relatively poor performance of the San Andres are: relative permeability hysteresis and changing rock wettability to a partially oil wet condition. It may be assumed that the effects of these phenomena are detrimental, but probably not sufficient to cause a change in plan for a full scale field development in the San Andres zone.³

A good match of observed and simulated data was obtained in both a pattern wide analysis and at a single interval in the observation well. It was informative to note that although the recovery from the San Andres 9th massive was low, the oil saturation at the observation well was reduced to about 10 percent. Also in Table 4, apparent pore volume in both reservoirs was larger than the design volume. Log analysis indicated that the actual pore-volume of the San Andres zone was significantly greater than estimated in the pilot design by showing that the CO₂ injection into the San Andres (9th massive) zone entered porosity stringers below the perforations.⁴

The gamma ray logs indicated the tracers to be very effective in giving response time and zone definition within each of the reservoirs. The number of responding layers was greater (and the layers thinner) than had been predicted based on conventional log and core data gathered during the pilot drilling phase. The effect of the thin-bed effects had to be calculated in determining the saturations in each layer.⁴ This ability to define responding layers and to group them according to their response times was helpful in developing the reservoir description used in the computerized simulations.³

Considering that residual oil saturations after waterflooding were 30 percent for the 6th zone and 40 percent PV for the 9th massive and that after the passage of the CO₂ front, oil saturation was 10 percent to 15 percent for both zones, the volumetric sweep efficiency was calculated to be 64 percent for the Grayburg (6th) zone and 28 percent for the San Andres 9th massive zone.³ The CO₂ utilization as shown in Table 4 was 8.8 and 14.1 mcf of CO₂ per barrel of incremental oil for the 6th and 9th zones, respectively.

CONCLUSIONS

Conclusion reached by the operator concerning the performance of the pilot CO₂ flood are:

- 1) The miscible CO₂ flood process can significantly reduce oil saturations and recover the mobilized oil in the 6th and 9th massive zones at Maljamar.
- 2) Both hysteresis and a change in rock wettability occurring during the CO₂ flood can explain the minimum water saturation, CO₂ injectivity, and relative permeabilities needed to duplicate the performance of the 6th and 9th massive zone pilots.
- 3) The water-alternating-gas (WAG) process should not be needed for CO₂ mobility control in this reservoir where oil saturations near waterflood residual exist.
- 4) The minimum water saturation and residual CO₂ saturation in the 6th and 9th massive zones were significantly higher than what was originally predicted.

Additional conclusions reached as a result of this review are:

- 1) The pre-pilot planning and engineering resulted in effectively obtaining data for computer simulation of the CO₂ flood design.
- 2) Interpretability of the inverted 5-spot pattern was improved by injection outside the pattern and use of logging observation wells.
- 3) Corrosion problems, well test problems, and oil handling problems arose during the operation of the pilot. Solution of these problems resulted in obtaining additional valuable information to improve design of a full-scale operation.

- 4) The continuity of the engineering and data accumulation throughout the entire pilot from the pre-planning through the final analysis resulted in timely, informative engineering reports of value to the industry concerning CO₂ flooding.

RECOMMENDATION

The concepts embodied by Conoco in the Maljamar pilot are recommended for other field pilots where timely, accurate process data is needed to design a field-scale project. Briefly, the small inverted 5-spot pattern reduced the time required and the quantity of CO₂ needed. Use of outside injection wells, together with the use of tracers, provided both the confinement of the CO₂ and an accurate flow distribution. Finally, and very importantly to the interpretation of the inverted pattern pilot, use of the fiberglass-cased logging monitor wells showed both which strata conducted injected fluids and how much oil, water, and CO₂ saturation changed in the conducting strata.

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3. Moore, J.S. and Clark, G.C., "History Match of the Maljamar CO₂ Pilot Performance", SPE/DOE Enhanced Oil Recovery Symposium, Tulsa, Oklahoma, April 17-20, 1988, SPE/DOE Paper No. 17323.
4. Albright, J.C., "Use of Well Logs To Characterize Fluid Flow in the Maljamar CO₂ Pilot", Journal of Petroleum Technology, August 1986, pp. 883-890.

TABLE 1 *
6TH ZONE RESERVOIR DESCRIPTION BASED
ON CO₂ PILOT HISTORY MATCH

Layer Properties

<u>Layer No.</u>	<u>Ø, fraction</u>	<u>h, ft</u>	<u>K, md</u>	<u>Øh, Fraction</u>	<u>Kh, Fraction</u>
<u>Well 359</u>					
1	0.121	4.536	19.750	0.178	0.300
2	0.121	6.804	15.386	0.267	0.350
3	0.121	14.140	7.407	0.555	0.350
<u>Well 360</u>					
1	0.127	4.452	16.621	0.250	0.303
2	0.127	6.230	13.500	0.350	0.344
3	0.127	7.098	12.186	0.400	0.353
<u>Well 361</u>					
1	0.129	2.954	42.243	0.095	0.300
2	0.129	9.604	15.157	0.309	0.350
3	0.129	18.550	7.850	0.596	0.350
<u>Well 362</u>					
1	0.126	3.682	27.543	0.195	0.300
2	0.126	4.760	24.850	0.251	0.350
3	0.126	10.500	11.264	0.554	0.350

Quadrant Properties

<u>Quadrant</u>	<u>Ø, Fraction</u>	<u>h, ft</u>	<u>K, md</u>	<u>Øh, Fraction</u>	<u>Kh, Fraction</u>
359	0.121	25.480	11.735	0.263	0.230
360	0.127	17.780	13.757	0.192	0.189
361	0.129	31.108	13.372	0.342	0.321
362	0.126	18.942	17.842	0.203	0.260

Total Kh = 1,297.5 md-ft
Total Øh = 11.741 ft

* From Reference 3

TABLE 2 *
9th MASSIVE ZONE RESERVOIR DESCRIPTION BASED
ON CO₂ PILOT HISTORY MATCH

<u>Layer Properties</u>					
<u>Layer No.</u>	<u>Ø, fraction</u>	<u>h, ft</u>	<u>K, md</u>	<u>Øh, Fraction</u>	<u>Kh, Fraction</u>
<u>Well 359</u>					
1	0.109	11.39	11.59	0.220	0.300
2	0.109	16.96	9.08	0.328	0.350
3	0.109	23.40	6.58	0.452	0.350
<u>Well 360</u>					
1	0.090	9.00	7.33	0.288	0.300
2	0.090	10.50	7.33	0.335	0.350
3	0.090	11.80	6.53	0.377	0.350
<u>Well 361</u>					
1	0.091	8.32	6.35	0.290	0.300
2	0.091	9.50	6.48	0.331	0.350
3	0.091	10.90	5.65	0.379	0.350
<u>Well 362</u>					
1	0.128	15.30	26.75	0.181	0.300
2	0.128	23.00	20.76	0.273	0.350
3	0.128	46.00	10.38	0.546	0.350

<u>Quadrant Properties</u>					
<u>Quadrant</u>	<u>Ø, fraction</u>	<u>h, ft</u>	<u>K, md</u>	<u>Øh, Fraction</u>	<u>Kh, Fraction</u>
359	0.109	51.75	8.50	0.258	0.200
360	0.090	31.30	7.03	0.129	0.100
361	0.091	28.72	6.13	0.119	0.080
362	0.128	84.30	16.18	0.494	0.620

Total Kh = 2,200.0 md-ft
Total Øh = 21.862 ft

* From Reference 3

TABLE 3 *
MALJAMAR FLUID PROPERTIES AT P = 2,600 psia, T = 90°F

Hydrocarbon

Specific Gravity	0.773
Viscosity	1.12 cp
Formation Volume Factor	1.23 res. bbl/STB
Gas: Oil Ratio	0.500 MCF/STB
Minimum Miscibility Pressure	1,315 psia
Compressibility	$0.15 \times 10^{-4} \text{ psi}^{-1}$

Brine

Specific Gravity	1.05
Viscosity	0.86 cp
Compressibility	$0.03 \times 10^{-4} \text{ psi}^{-1}$

CO₂

Specific Gravity	0.86
Viscosity	0.084 cp
Compressibility	$0.50 \times 10^{-4} \text{ psi}^{-1}$

6t		0.8
9t	meter	0.7

* From Reference 3

TABLE 4 *
RESULTS OF MALJAMAR PILOT HISTORY MATCH

	<u>6TH ZONE</u>		<u>9TH MASSIVE ZONE</u>	
	<u>Field</u>	<u>Model</u>	<u>Field</u>	<u>Model</u>
Pore Volume, res. bbl	88,200*	133,500	111,600*	247,130
OOIP, STB	51,800*	78,400	74,102*	164,090
CO ₂ Injected				
MCF	70,070	70,320	87,200	87,600
PV, %	30.6*	20.3	30.1*	13.6
Inc. Oil Produced				
STB	8,701	8,035	7,487	6,210
% OOIP	16.8	10.2	10.1	3.8
CO ₂ Produced				
MCF	16,900	20,960	6,940	5,791
% of Injected	24.1	29.8	8.0	6.6
CO ₂ Utilization				
MCF/inc. STB	8.1	8.8	11.6	14.1
0.3848 $\frac{\text{res. bbl CO}_2}{\text{MCF CO}_2}$ at 2600 psia		Sorm = 0.06 w = 0.8		Sorm = 0.06 w = 0.7

* Design values

* From Reference 3

FIGURE. 1

FIGURE. 2

Typical log with producing zones, Maljamar CO₂ pilot.

FIGURE. 3

FIGURE. 4

FIGURE. 5
Sixth Zone production history.

FIGURE. 6
Injection history for the Sixth Zone.

FIGURE. 7 Ninth Massive production history.

FIGURE. 8

Maljamar CO2 Pilot - 6th Zone

FIGURE. 9

Maljamar CO2 Pilot - 6th Zone

FIGURE. 10

Maljamar CO2 Pilot - 9th Massive Zone

FIGURE. 11

Maljamar CO2 Pilot - 9th Massive Zone

FIGURE. 12

FIGURE. 13

FIGURE. 14