“Application of Cyclic CO2 Methods in an Over-Mature Miscible CO2 Pilot Project – West Mallalieu Field, Lincoln County, MS”

FINAL TECHNICAL REPORT

BOYD STEVEN GETZ

SEPTEMBER 2001

U.S. Department of Energy Grant/Cooperative Agreement
No. DE-FG26-99C15243

J.P. OIL COMPANY, INC.
22034 ROSEDALE HWY
BAKERSFIELD, CA 93312

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 of 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.

SPECIAL NOTE

This report details the results of one completed experiment. Denbury Resources purchased the subject Field shortly after the last Technical reports were submitted. The Sale was finalized in April 2001. No additional technical information was attained since the last reporting period. Although we had planned to continue the cyclic CO2 experiments at West Mallalieu Field these have been indefinitely deferred due to the sale.

ABSTRACT

This progress report summarizes the results of a miscible cyclic CO2 project conducted at West Mallalieu Field Unit (WMU) Lincoln County, MS by J.P. Oil Company, Inc. Lafayette, LA.

Information is presented regarding the verification of the mechanical integrity of the present candidate well, WMU 17-2B, to the exclusion of nearby more desirable wells from a reservoir standpoint. Engineering summaries of both the injection and flow back phases of the cyclic process are presented.

The results indicate that the target volume of 63 MMCF of CO2 was injected into the candidate well during the month of August 2000 and a combined 73 MMCF of CO2 and formation gas were recovered during September, October, and November 2000. The fact that all of the injected CO2 was recovered is encouraging; however, only negligible volumes of liquid were produced with the gas.

A number of different factors are explored in this report to explain the lack of economic success. These are divided into several groupings and include: Reservoir Factors, Process Factors, Mechanical Factors, and Special Circumstances Factors. It is impossible to understand precisely the one or combination of interrelated factors responsible for the failure of the experiment but I feel that the original reservoir quality concerns for the subject well WMU 17-2B were not surmountable.

Based on the inferences made as to possible failure mechanisms, two future test candidates were selected, WMU 17-10 and 17-14. These lie a significant distance south of the WMU Pilot area and each have a much thicker and higher quality reservoir section than does WMU 17-2B. Both of these wells were productive on pumping units in the not too distant past. This was primary production not influenced by the distant CO2 injection. These wells are currently completed within somewhat isolated reservoir channels in the Lower Tuscaloosa “A” and “B-2” Sands that overlie the much more continuous and much larger Lower Tuscaloosa “C” Sand reservoir. The current proposal is to not only cycle the Lower Tuscaloosa “C” Sand in these wells but to also test the process on these discontinuous “A” and “B-2” reservoir pools to determine if miscible cyclic processes are applicable where continuous CO2 operations are not feasible.

Additional modifications to the experiment are also discussed and a schedule for 2001 and 2002 operations are presented.

TABLE OF CONTENTS

PROGRESS REPORT

"Application of Cyclic CO2 Methods in an Over-Mature Miscible CO2 Pilot Project – West Mallalieu Field, Lincoln County, MS"
U.S. Department of Energy Grant/Cooperative Agreement No. DE-FG26-99C15243

Please refer to **Appendix I**: PLANNING DOCUMENT FOR CYCLIC CO2 APPLICATION AT WEST MALLALIEU FIELD – *NEW DOE PROJECT TITLE:* "Application of Cyclic CO2 Methods in an Over-Mature Miscible CO2 Pilot Project – West Mallalieu Field, Lincoln County, MS" Boyd Getz, 11/2/99 for background on this project.

EXECUTIVE SUMMARY

The first phase of the U.S. Department of Energy Grant/Cooperative Agreement No. DE-FG26-9C15243 has been essentially completed. This progress report summarizes the results of the miscible cyclic CO2 experiment conducted on well WMU 17-2B at West Mallalieu Field Unit (WMU) Lincoln County, MS by J.P. Oil Company, Inc. Lafayette, LA.

The first cyclic candidate; an original West Mallalieu Unit CO2 pilot well, WMU 17-2; was found to be in unsuitable mechanical condition. Fortunately two additional observation wells were available adjacent to the WMU 17-2 well location. Unfortunately, however, the only viable well from a mechanical standpoint of these two substitute wells had very poor local reservoir quality characteristics and it was questionable as to whether that the Company should proceed with the experiment at this location. It was decided that the first experiment would be attempted although the reservoir risk of failure was acknowledged as significant.

The well injected tested at low rates and with high injection pressure with lease water and was therefore acidized. The final injection rate after acid was 1.6 barrels per minute at 2,600 psig. The well was equipped and CO2 injection was initiated in August 2000. Over a month period the target CO2 volume of 63 MMCF was placed during the "Huff" Phase of the experiment. Researchers recommended that due to the risk of excessive pressure diffusion that the injection time period should suffice as the "Soak" period and therefore the test well was placed in the "Puff" mode as soon as possible.

A combined 73 MMCF of CO2 and formation gas were recovered during September, October, and November 2000. The fact that all of the injected CO2 was recovered is encouraging; however, only negligible volumes of liquid were produced with this gas.

A number of different failure mechanisms are considered to account for the lack of economic success. These are divided into several groupings and include: Reservoir Factors, Process Factors, Mechanical Factors, and Special Circumstances Factors. It is impossible to determine precisely the one or combination of interrelated factors responsible for the failure of the experiment but, I feel that the original reservoir quality concerns for the subject well WMU 17-2B were not surmountable.

Based on the inferences made as to possible failure mechanisms, two future test candidates were selected, WMU 17-10 and 17-14. These lie a significant distance south of the WMU Pilot area and each have a much thicker and higher quality reservoir section than does WMU 17-2B. Both of these wells were productive on pumping units in the not too distant past. This area of the Field most likely has not been influenced by the distant CO2 injection. These wells are currently completed within somewhat isolated reservoir pools, Lower Tuscaloosa "A" and "B-2" Sand channels, which overlie the continuous and much larger Lower Tuscaloosa "C" Sand reservoir. The current proposal is to not only cycle the Lower Tuscaloosa "C" Sand but to also test the process on these discontinuous reservoir pools to determine if the miscible Cyclic process has an application where continuous CO2 operations are not feasible.

EXPERIMENTAL METHOD

The experimental activity that the Company is conducting at WMU is the application of the miscible cyclic CO2 process. This is perhaps better known as "CO2 huff 'n' puff." It involves injecting a slug of CO2 into an oil well – the "huff" phase, allowing the CO2 soak into the reservoir for period of time, then returning the well to production - the "puff" phase. Technical and economic successes using this process are not uncommon at immiscible or near-miscible conditions. Immiscible or near-miscible conditions are those in which the reservoir pressure is less than the minimum miscibility pressure (MMP).

Miscible condition Field experiments, where the reservoir pressure is significantly greater than MMP, are very uncommon. At least part of the reason for this lack of history appears to be that such a large volume of CO2 is required to contact a significantly large reservoir volume under miscible conditions, that the high cost of CO2, high cost of CO2 transportation, high cost of CO2 compression and handling facilities, other logistical constraints, and unfamiliarity and inexperience with CO2 operations has rendered the proposition infeasible. At WMU these constraints are not limiting factors.

RESULTS AND DISCUSSION

WELL SELECTION AND PREPARATION

The first proposed field experiment of the miscible cyclic CO2 process, "CO2 huff 'n' puff," has been commenced at West Mallalieu Field Unit (WMU). The application was performed on well WMU 17-2B. At the WMU 17-2 location, there exists three potential candidate wells WMU 17-2, the original CO2 Pilot Project producer and two observation wells, WMU 17-2A and WMU 17-2B. Engineering determined that the original pilot producer WMU 17-2 was mechanically unsuitable for the test due to multiple fish in the hole; therefore, the observation well with the best reservoir section, WMU 17-2A, was selected as an even more attractive substitute from a sand quality stand point. It was reentered on February 14, 2000. Unfortunately, it was found that this well had a casing hole, and operations were suspended on February 24, 2000. The only remaining mechanically viable well at the WMU 17-2 location was now WMU 17-2B. Geology was apprehensive about this particular candidate since the Lower Tuscaloosa “C” sand face appeared to be significantly cemented through the middle two-thirds of the section as observed in the original Resistivity log; however, the cumulative primary production for this well was documented as 229 MBO/ 19 MBW/ 74 MMCFG from December 1953 through February 1961 when it was originally abandoned. The Company decided to proceed with WMU 17-2B as the first cyclic CO2 candidate.

WMU 17-2B was circulated clean and the casing tested. The Lower Tuscaloosa “C” Sand was perforated and the completion swab tested during a work over from February 24 to March 16, 2000. Two hundred-fifty barrels of water and no oil were recovered during a day and a half of swab testing. This recovery is typical for a slow-to-respond producer in a field that has been swept to residual oil saturation by a strong natural water drive. WMU 17-2B was then permitted for CO2 cyclic injection.

Permits were acquired, and a work over to convert the well to CO2 injection took place from June 19 to June 26, 2000. The completion was tight on injection test with less than ¼ barrel of lease water per minute of injectivity at 3,000 psig. The sand face was broken down with acid at 4,900 psig. The final rate after acid was 1.6 barrels per minute at an injection pressure of 2,600 psig. The well was equipped down-hole and at the surface and the casing retested. During the next month an injection line for the CO2 was installed.

THE “HUFF” PHASE

The injection phase of the Cyclic CO2 project was initiated on August 2, 2000. The initial injection rate was 1,250 MCFPD at an injection pressure of 2,350 psig. This was somewhat of a disappointing rate since the Company was hoping to achieve rates comparable to the pilot injection wells, on the order of 6,000 to 12,000 MCFPD. This was undoubtedly due to the relative tightness of this particular sand face. By August 13, 2000 the injection rate had declined to 900 MCFD at an injection pressure of 2,420 psig. On August 14, 2000 the injection pressure was increased to 2,530 psig and the rate consequently ramped up to 3,300 MCFPD. By August 29, 2000 the total target volume of 63 MMCF of CO2 had been placed in the “huff” phase of this first miscible cyclic CO2 experiment. The tubing pressure remained at 1,800 psig over the next two days during which time the well was reconfigured for the “puff” flow test phase.

THE “PUFF” PHASE

On August 31, 2000 the well was flowed back at a rate of 2,330 MCFD and no liquid on a 14/64” choke. On September 5, 2000 the choke was decreased to a 9/64” in an attempt to maintain backpressure on the well. This was recommended in the literature as advantageous. The well flowed at 1,200 MCFD and still no liquid. On September 8, 2000 the CO2 rate remained the same and 10 BW were metered. On September 9, 2000 the CO2 rate remained the same and 3 BO and 30 BW were metered. After that only minor volumes of liquid were detected as the CO2 rate and pressure slowly declined. By November 12, 2000, 73 MMCF of gas had been produced back and only 6 BO and 41BW. The final flowing tubing pressure was measured at 1,010 psig with a rate of 300 MCFD. By November 13, 2000 the well ceased flowing into the high pressure CO_2 recovery system with a tubing pressure of 1,000 psig.

The recovery of 10 MMCF of additional gas than what was originally injected can be explained at least in part by the natural gas component of the recovered gas which averages about 6% at Little Creek Field Unit where full-field CO_2 drive operations within the Lower Tuscaloosa are being conducted. This natural gas component percentage could be significantly greater at WMU in this newly completed well. Meter error and possible CO_2 contribution from the WMU pilot project injection are also possible contributors.

The well will be placed into the low pressure CO_2 recovery system where it can continue be tested. The experiment on this first well is not entirely over, but it does appear to be a case of "the operation was a success, but the patient died." We did inject the CO_2; we did get it back; the only problem is that negligible liquid came with it.

POSSIBLE FACTORS CONTRIBUTING TO EXPERIMENTAL FAILURE

There are a number of possible factors contributing to the failure of this experiment and these can be broken into categories. The actual failure mechanism is probably a combination of several interrelated factors.

Reservoir Factors

1) The reservoir section in WMU 17-2B was too tight for the Cyclic CO_2 process to be effective. This problem may have caused or influenced some of the other factors listed here.
2) Too thin of a net pay section. With the cemented portion of the sand face the actual net pay in WMU 17-2B is significantly less than the net pay in either of the more desirable adjacent candidates, WMU 17-2 or WMU 17- 2A.
3) The injection rates achieved were too low for the process to be effective at miscible conditions due to the lower permeability sand face.
4) Low injectivity necessitates a longer injection period to achieve the desired volume. This too may have been a detrimental factor.
5) The reservoir section injected into is somehow stratigraphically isolated from the main part of the reservoir. This isolation is not apparent from the existing data but could be related to the cementation observed.
6) The injected volume migrated out-of-zone. The "D" Sand below the "C" Sand is not present, the "B-3" Sand is completely cemented, and the Lower Tuscaloosa reservoirs above the "B-3" Sand are not well developed at all; therefore, this is an unlikely scenario.

Process Factors

1) Too short of a soak period to allow mixing of the mobilized oil front back towards the well bore.
2) Too long of an injection period pushing the mobilized oil too far always from the well bore to produce it back.
3) Too much injection pushing the oil too far always from the well bore to produce it back.
4) Too little injection resulting in a slug that was too small to contact oil and (or) CO_2 saturated areas in the proximity of the well bore.

5) The miscible process under these conditions is so efficient that the oil was stripped away from the near well bore area forming CO_2/oil bank that will not readily remix with the pure CO_2 bank at the well bore.

Mechanical Factors

1) Too small of a choke preventing achievement of sufficient velocity to flow liquids up the tubing. Although backpressure on the well is recommended in the literature, this may have impeded liquid recovery.
2) The injection rates achieved were too low for the process to be effective, although the system limits were being approached.

Special Circumstances Factors

1) WMU 17-2 was recognized as a slow-to-respond producer as compared to other Pilot Project wells. This was thought to have been due to the preferential migration and formation of CO_2 channels to other wells which could not be altered by conventional means. On the other hand, WMU 17-2 may have been a slow-to-respond producer for other reasons such as formation damage, a plugged gravel pack, and (or) stratigraphic isolation from the injection wells. In these situations cyclic CO_2 applications might not improve the situation.
2) The area, although not apparent from production histories, is already swept by CO_2. The original pilot producer WMU 17-2 may have formation damage, a plugged gravel pack, and (or) a casing leak that has inhibited a normal continuous CO_2 drive production well response.
3) Diffusion and loss of Pilot Area reservoir pressure due to CO_2 purchase cut backs in June 1998 and essential shut-in of the Field and elimination of CO_2 purchases in November 1998.
4) Loss reservoir pressure due to the Pilot Project being brought back on line in February 2000 on CO_2 recycle mode only with no make-up CO_2 purchases to replace the liquid withdrawals.

We can explore each of these factors and their interrelations in detail, but that is probably beyond the scope of this progress report. I have a feeling that the original reservoir quality concern that the WMU 17-2B sand face was just too tight to get a representative test of the miscible cyclic CO_2 process is probably the most significant factor. Also since the sand face was tight one can make a case that this area maybe at least partly stratigraphically isolated from the main part of the reservoir. The tight section lies just north-north-west of the original WMU 17-2 pilot producer and is a potential CO_2 migration barrier from its next nearest injection well WMU 8-15A. Perhaps this is a reason as to why WMU 17-2B is a slow-to-respond producer.

FUTURE TESTCANDIDATES

Of the remaining two original proposed candidate wells, WMU 17-4 and WMU 17-14, Engineering feels that WMU 17-14 is of lower risk from a mechanical standpoint. WMU 17-14 is also a significant distance from the Pilot Area and although the costs for conducting the cyclic CO_2 experiment will be somewhat higher due to the necessity to install a longer CO_2 pipeline, many of the factors of concern in the first experiment will be mitigated. Also WMU 17-14 is currently completed within two small, fairly isolated reservoirs These include the Lower

Tuscaloosa "A" and "B-2" Sand channels which lie stratigraphically just above the "C" Sand. This situation provides an opportunity to conduct an experiment within these discontinuous reservoirs pools to determine if the miscible Cyclic CO2 process has an application where continuous CO2 operations are not feasible.

WMU 17-10 is also another existing unplugged well and it lies northeast of WMU 17-14, a little closer to the Pilot operation. WMU 17-10 represents another viable cyclic candidate. This well may be tested rather than WMU 17-14 if it appears to be a better candidate. It too is completed within the "B-2" Sand and provides an opportunity to test an isolated reservoir pool with the miscible Cyclic CO2 processes.

Both wells have thick and permeable "C" Sand sections underlying their current completions. Either of these wells will provide an excellent opportunity to test the process on the Lower Tuscaloosa "C" Sand extensive reservoir pool.

FACTORS TO IMPROVE THE PROBABILITY OF SUCCESS

The following is a list of ways to mitigate the possible failure mechanisms for WMU 17-2B by conducting further Cyclic CO2 experiments on new candidate wells WMU 17-10 or WMU 17-14:

Reservoir Factors

1) Significantly improved reservoir quality. Whole core data exists for both wells to verify this.
2) Significantly greater "C" Sand net pay thickness.
3) Factors 1) and 2) will enable a higher injection rate to be achieved.
4) A higher injection rate will result in a relatively shorter injection time.
5) There appears to be no cementation problem or stratigraphic anomalies in the area in the Lower Tuscaloosa "C" Sand; therefore, the risk of stratigraphic isolation is minimal.
6) Testing the "B-2" isolated pool will lessen the risk of CO2 pressure diffusion.

Process Factors

1) Increase the soak period to allow mixing of the mobilized oil front back towards the well. In the previous experiment the well was returned to production as soon as possible after the injection phase. This was due to concerns that the CO2 pressure would diffuse and dissipate into the reservoir such that the "puff" stage would be short lived. This time the Company will determine a shut in tubing pressure threshold at which point the well will be opened to flow. This will enable a longer a soak period to be realized. The maximum soak period will be set at 4 weeks as recommended in the literature.
2) The relative injection period should be greatly reduced due to the increased sand thickness and permeability.

Mechanical Factors

1) Produce back test wells on a larger choke to increase flow velocity to bring more liquids up the tubing.

Special Circumstances Factors

1) The test candidates are far enough away that there should be no CO_2 in the area from previous out-of-pattern CO_2 migration from the Pilot Project; therefore, these unknowns should be eliminated.

SCHEDUAL FOR NEXT PHASES OF EXPERIMENT

First Quarter 2001

a. Permit well for "B-2" Sand injection.
b. Prepare well for injection.

Second Quarter 2001

a. Lay pipeline.
b. Inject CO_2 slug into "B-2" Sand reservoir.
c. Soak period.
d. Initiate production test for "B-2" Sand reservoir.

Third Quarter 2001

a. Complete production test for "B-2" Sand reservoir.
b. Permit well for "C" Sand injection.
c. Prepare well for injection.
d. Initiate CO_2 injection into "C" Sand reservoir.

Forth Quarter 2001

a. Complete CO_2 injection into "C" Sand reservoir.
b. Soak period.
c. Initiate production test for "C" Sand reservoir.

First Quarter 2002

a. Complete production test for "C" Sand reservoir.
b. Final report.

CONCLUSION

Although the Company is discouraged with the results of this first attempt, it remains resolved to give the miscible cyclic CO_2 process another try at WMU. The fact that the injected CO_2 was recovered is encouraging. This time the Company will attempt to eliminate as many of the postulated factors contributing to the failure of the WMU 17-2B experiment as possible.

Assuming that future WMU tests are successful and an average CO_2 utilization of around 3 MSCF/STB can be attained, then substantial reserves in an entirely new reserve category may be defined not only at WMU and along the entire Lower Tuscaloosa trend but also in many other areas where conventional methods of secondary and tertiary recovery area infeasible.

APPENDIX I

Boyd Getz 11/2/99

PLANNING DOCUMENT FOR CYCLIC CO2 APPLICATION AT WEST MALLALIEU FIELD – *NEW DOE PROJECT TITLE:* "Application of Cyclic CO2 Methods in an Over Mature Miscible CO2 Pilot Project – West Mallalieu Field, Lincoln County, MS"

A detailed plan, AFE's, permits, and sets of procedures are required to insure the successful implementation of DOE grant (DE-FG26-99BC15243) for CO2 cyclic operations at West Mallalieu Field Unit (WMU). This grant was transferred from planned work at Little Creek Field Unit (LCU) which was halted due to sale of the Field to Denbury Resources Inc., Plano, TX. Since the Company, J.P. Oil company, Inc. (JPO), will be testing an experimental stimulation/production technique and has committed to using partial Government funding, then the documentation of workover and operational events, field data, costs, and production results are essential. This project along with the Federal funding will enable JPO to test a methodology that may transform WMU into a valuable asset.

The process that the Company will be testing at WMU is the application of cyclic CO2 operations. This is perhaps better known as "CO2 huff 'n' puff." It involves injecting a slug of CO2 into a producing oil well – the "huff" phase, allowing the CO2 soak into the reservoir for period of time, then returning the well to production - the "puff" phase. Technical successes using this process are not uncommon; however, it is not a widely employed technique due to the high cost of CO2, facilities or other logistical constraints, or unfamiliarity and inexperience with CO2 operations.

West Mallalieu Field History

West Mallalieu Field is located in Lincoln County, MS and was discovered by Chevron in August 1944. The discovery well, W. C. Douglas #1, located in Section 10-T6N/R8E, had an initial production of 374 BOPD of 38.1-degree API gravity oil with a 0.2 % water cut and GOR of 396 SCF/STB. Several follow–up wells were dry and development of the discovery area remained dormant until August 1946 at which time Chevron completed the M. P. Daniels #1 located in Section 17-T6N/R8E which identified the much larger western accumulation of the Field. Development accelerated rapidly thereafter and peaked in 1949 with 94 wells on production. A total of 185 wells at 40-acre well spacing were drilled for the Lower Tuscaloosa objective resulting in 126 producers and 59 dry holes. By December 1978 all wells had been plugged except for three producers and two shut-in wells with remaining recoverable reserves of only 180 MBO. Cumulative primary production for West Mallalieu as of January 1979 was 34.5 MMBO, 13.2 MMBW, and 11.5 BSCFG. No water flood project was required to develop the Field due to the existence of a strong natural water drive.

Shell purchased the all but abandoned West Mallalieu Field in 1978 in an attempt to expand its tertiary recovery reserve resource base and to further capitalize on the tremendous reserves of CO_2 discovered in Pisgah Field and other CO_2 fields in the Northeast Jackson Dome area. The Little Creek Field pilot CO_2 flood, which was conducted from 1973 through 1978, had resulted in recovery of over half of the residual oil in place and was considered a great technical success thereby opening the way for a field-wide expansion project. Therefore, the West Mallalieu Field purchase was made in anticipation of implementing another CO_2 pilot to field-wide expansion project.

By 1982, when the West Mallalieu Field Unit (WMU) was ultimately formed, only one 20-30 BOPD well remained on production, whereas nearly all of the other wells had been plugged and abandoned. By mid-1982 Shell had reentered a number of wells and drilled some grass-roots evaluation wells. The new completions produced essentially all water thus demonstrating that the reservoir had been produced to effective residual oil saturation conditions.

CO_2 injection into a four, inverted 5-spot pattern, pilot project was initiated in November of 1986. Five water injection wells were installed on the periphery of the pilot patterns to confine the injected CO_2. By the last quarter of 1988, nearly two years later, only 3 of the pilot producers had responded. At that point injection of the barrier water was terminated. By late 1988, oil was tested from several of the shut-in water injection wells, and these where converted to production wells early in the following year. This conversion resulted in increased fluid production, CO_2 injection, and accelerated pilot response. Oil production peaked to 1,700 BOPD by mid 1989 and proceeded to take a sharp, ~50%, decline during the following year, followed by a ~40% decline the year after. Since mid 1991 the decline is holding steady at less than 10%. The Field is capable of sustained production rates of 200-300 BOPD but is currently shut-in as uneconomic.

As of January 1998 West Mallalieu Field has produced in excess of 2.0 MMBO of CO_2 enhanced recovery reserves.

Little Creek and West Mallalieu Fields - Analogous Characteristics

The productive intervals at both Little Creek and West Mallalieu Fields are sand channels, point bars, and overbank deposits of the Upper Cretaceous age Lower Tuscaloosa Formation. The Lower Tuscaloosa reservoir is found at similar measured depth ranges in both fields, about 10,250-10,750 ft. The structural dip at both fields is very low, <1 degree, and both pools represent combination structural-stratigraphic traps.

The Lower Tuscaloosa Formation was deposited in a fluvial-deltaic depositional environment. Both fields have similar provenance, the distant northwesterly Ochita Mountains; therefore, petrophysical characteristics are approximately the same. Each field was developed on a 40-acre well spacing plan. Little Creek Field had a peripheral water flood project installed four years after discovery and was subsequently water flooded to an effective residual oil saturation. Whereas there was no need to install a water flood at West Mallalieu Field due to the existence of a strong natural aquifer drive which maintained primary production to continue to an effective residual oil saturation; therefore, both fields' pre-CO_2 residual oil saturation conditions are analogous. In other words essentially all current recovery at either field is incremental oil that is attributable to the CO_2 enhanced tertiary recovery process.

Both fields involve continuous miscible CO_2 injection projects installed by Shell, and although the Little Creek pilot was eventually expanded to include about half of the field area, the West Mallalieu pilot was expanded by only one pattern due to poor economics. The West Mallalieu pilot has been shut in periodically over the last 1-½ years due to extremely low oil prices.

Both fields are plagued with a number of wells that are slow-to-respond to CO_2 injection and are nearby or adjacent to wells that have gone through a full cycle to peak oil response and eventual CO_2 breakthrough.

WMU CO2 Cyclic Candidates

Candidate wells of first choice include WMU 17-2, 17-4, and 17-14 (Randell 6). Detailed histories and well bore diagrams are needed for these wells. Other good candidates exist from a reservoir/enhanced oil recovery standpoint, but these have been eliminated from the first round of testing due to mechanical conditions that are anticipated to require capital-intensive workovers to repair. The first two candidates, WMU 17-2 and 17-4, are on either side of the current best Field producer, WMU 17-3. All three of these wells lie just upstructure of pilot CO_2 injection wells WMU 8-11-2 and 8-15-2. Patterns WMU 8-11-2 and WMU 8-15-2 have had an estimated cumulative CO_2 injection of 28 BCF or 4.2 pore volumes (PV's) and 31 BCF or 3.7 PV's respectively. These injection values are is as high as the most over mature patterns at LCU and twice as much as the LCU average. We are currently evaluating the volume of produced CO_2 within the pilot patterns in an effort to ascertain the volume and location of unrecovered CO_2 that may have or is currently migrating towards these and (or) other peripheral area wells.

WMU 17-3's weighted average annual production for mid 1997 to mid 1998 is 118BOPD/489BWPD/1,247MSCFG – 242 days on. Its original utility within the CO_2 pilot project was as a barrier water injection well during which time 227 MBW was injected. Its production back in 1989 peaked at ~550BOPD/500BWPD/2,500MSCFG when it was first placed on production in conjunction with the pilot project. It is also known to have had major mechanical problems that may have inhibited and/or will prematurely end the well's significant out-of-pattern response. Neither WMU 17-2 nor 17-4 have demonstrated a major CO_2 response as of yet; however, it is apparent that a CO_2 driven oil bank exists within the subject area that is not being affectivity drained. The cyclic CO_2 process will hopefully catalyze a CO_2 flood response. Table I lists the pre and post CO_2 cumulative production for the subject wells.

TABLE I. PRODUCTION DATA WMU 17-2, 17-3,and 17-4

WELL	Pre-CO2 CUM MBO	Pre-CO2 CUM MBW	Pre-CO2 CUM MMSCF	Post-CO2 CUM MBO	Post-CO2 CUM MBW	Post-CO2 CUM MMSCF
17-2	202	21	68	43	161	539
17-3	591	123	232	188	1,108	3,676
17-4	478	167	193	10	168	252

Candidate WMU 17-14 (Randell 6) is the injector spot for the first proposed inverted nine spot expansion pattern. This pattern is located far enough away from the existing over-processed pilot that it is still estimated to contain from 0.8 to 2.5 MMBO of CO_2 enhanced recovery reserves. These reserves exist within the Lower Tuscaloosa "C" Sand reservoir, which is the main producing member of a five productive sand lobe package at WMU. This well has been pumped in the recent past and is one of the few wells located outside of the pilot area that remains unplugged. Construction of a one-mile long high-pressure pipeline is necessary for this well, and it is more likely to require artificial lift to sustain production than WMU 17-2 or 17-4.

Near Term Procedures and Operational Considerations

1) Commence well permitting immediately on the proposed cyclic candidate wells. Perhaps we can go to the MS State Oil and Gas Board to get an exemption from some of the permitting requirements involved in this sort of operation.

2) Request permits from the local air quality authority to vent CO_2 as a backup measure if CO_2 recycle is not feasible.

3) Review the mechanical condition of the candidate wells and design workover procedures to insure the best implementation of the cyclic program.

4) Review the operational requirements of the proposed work and design a program to implement the project.

5) Prepare programs and AFE's for the above work.

6) Submit operational plans and formally request an expense advance from the DOE.

7) Reactivate the field. Several wells require paraffin cutting and possible hot oiling.

8) Prepare an integrated plan for improved operations at WMU including strategic water injection, capital projects, and expansion plans.

Past Evaluation of the Cyclic CO2 Process

Field performance data gathered and analyzed by researchers G. A. Thomas and T. G. Monger-McClure in a paper entitled "Feasibility of Cyclic CO_2 Injection for Light-Oil Recovery," in *SPERE* (May 1991) pgs.179-184, reveal several important trends. The database that was evaluated consisted of 106 single-well cyclic CO_2 tests conducted by major and independent oil companies within 14 oil fields in Louisiana and Kentucky. Of these, 90% demonstrated incremental oil production. Eight of the tests were failures due to mechanical problems experienced while injecting CO_2. For these projects a CO_2 utilization cutoff of 3 MSCF/STB was adopted to differentiate the economically successful projects from the "unsuccessful" projects. However, the costs associated with these tests would have been substantial considering the fact that the CO_2 was brought in on tanker trucks in most cases. Of the wells that recovered incremental oil during the CO_2 cycle process, 90% had a CO_2 utilization of <3MSCF/STB. The advantage that JPO has at WMU for our own cyclic CO_2 field tests is our CO_2 operations experience, existing CO_2 infrastructure and equipment, and a relatively inexpensive source of CO_2.

Project Performance Parameters

G. A. Thomas and T. G. Monger-McClure used four key performance parameters to evaluate these projects as indicated:

1) Incremental Oil – The increase in recovery over a baseline decline curve analysis.

2) CO_2 Utilization – The volume of CO_2 injected in MSCF divided the estimated incremental oil production.

3) CO_2 Reservoir Utilization – The volume of CO_2 injected in cubic feet measured at reservoir conditions divided the estimated incremental oil production.

4) Stimulation Ratio – The average production rate for the first month of post-CO_2 response divided by the average monthly oil production rate before CO_2 injection.

Key Conclusions Drawn from the Cyclic CO2 Studies by G. A. Thomas and T. G. Monger-McClure:

1) The incremental oil response is proportional to the volume of volume of CO_2 injected. The maximum economic slug size for any given field application may be determined by the balance between site-specific CO_2 costs and availability, work-over costs, and field-tested utilizations.

2) Production response improves for wells with thicker pay intervals.

3) CO_2 contacted oil is recovered more efficiently at higher reservoir pressures as long as miscible conditions are avoided. The target treatment radius may be increased as reservoir energy increases.

4) Average estimated CO_2 migration radius was estimated to be 73 ft for 30 successful tests and 144 ft for 10 tests with CO_2 utilizations greater than 5 MSCF/STB.

5) The optimum CO_2 soak period is about 1 month. The benefit of an extended soak period illustrates the importance of diffusion of CO_2 into the reservoir to the cyclic process.

6) The oil cut was improved by opening wells on a small choke and maintaining backpressure.

7) The cyclic CO_2 process does not require a high remaining oil saturation to be effective and is well suited to fields with high water cuts. During the production phase of the cyclic process reduced water cut was noted in nearly all of the tests. This observation suggests that reservoir relative permeability is affected in a beneficial way.

8) The observations that improved performance is obtained with an extended soak period, that back pressure is beneficial, and that there is a relationship between incremental oil and oil swelling, suggest that the enhanced oil-recovery mechanisms are more associated with phase behavior effects rather than reservoir repressurization.

9) CO_2 production and stimulated oil production rates were observed in wells offsetting the cyclic CO_2 test wells.

10) For a small group of wells there was a second cyclic of CO_2 that was conducted. Most of these tests demonstrated some performance decline from the first cycle.

11) For the successfully implemented field tests, the average CO_2 utilization was 1.3 MSCF/STB.

Specific Considerations for WMU

1) The Field is currently shut in and should be fully reactivated when the project is implemented.

2) The cyclic CO_2 process works best at sub-miscible pressure conditions. Minimum miscibility pressure (MMP) at WMU is ~3,600psi which is 900psi lower than the MMP for LCU of 4,500psi. The WMU Lower Tuscaloosa reservoir pressure is currently between 4,000 to 5,000psi. This indicates that there is no possibility of injecting at sub-miscible pressure conditions; however, since reservoir pressure is high, the cyclic CO_2 process will be more efficient.

3) Pressure-monitoring equipment needs to be operational at each test well site and at offset wells that might be affected by the process.

4) During the injection phase of the project, injection pressure and rate data from the subject wells should be documented at least once a day.

5) During the soaking and producing phases of the project, shut in and producing pressure and rate data from the subject wells should be taken at least once day and more frequently at the critical stages.

6) It will be critical to maintain enough backpressure during the soak period such that the wells can be produced without requiring artificial lift installation. One unfortunate difference between this project and the original LCU project is that there is neither a low-pressure CO_2 recycle nor ELPS system in the field; therefore, intermediate compression from the separator to the high-pressure recycle system will most likely be required. We will also need a permit to vent CO_2 as a backup measure. CO_2 cyclic well candidate WMU 17-14 may require artificial lift as previously noted.

7) Corrosion inhibition is another critical factor to consider. After the recommended volume of CO2 has been injected into each well it should be completely displaced from the well bore into the reservoir with inhibitor oil. During the production phase a hole should be shot into the tubing and continuous inhibition initiated ASAP.

8) Empirical evidence indicates that kill fluids have damaged productivity in the Lower Tuscaloosa reservoir. From our experience at LCU, most of the wells that were killed with water for workovers, especially the heavier water, induced a significant production loss and delay. This lost productivity is most likely the result of formation damage mechanisms; therefore, the Company should take all reasonable measures possible to avoid a repeat of this at WMU.

9) An advantage for candidates WMU 17-2 and 17-4 is that there should be enough CO2 saturation and injected CO2 pressure in the nearby reservoir environment to catalyze and sustain the cyclic response.

10) To put the field test average CO2 utilization of 1.3 MSCF/STB from the research projects into proper perspective, consider recent purchase CO2 utilization at LCU of 20,000 MSCF / 1,500 STBD = 13.3 MSCF/STB, an order of magnitude higher. Better yet, consider total injected CO2 utilization at LCU of 160,000 MSCF / 1,500 STBD = 106.7 MSCF/STB, almost two orders of magnitude higher. Therefore the cyclic CO2 process has the capacity of being much more efficient and cost effective than a CO2 flood from a capital project perspective. The process has application in isolated pools where CO2 flooding is not feasible, as well as to enhance active CO2 drive projects.

WMU Cyclic CO2 Volume Calculation

Since CO2 source is not a limiting factor, reservoir pressure is relatively high, and continuous CO2 drive mechanisms will be active adjacent to most test sites, then the maximum injection test radius of 150 ft is recommended. The volume of CO2 for each cyclic treatment may therefore be calculated for each well with the following expression:

$$\mathbf{CV = P\ r^2 * H * F * K * Sco_2 * LC}$$

P = 3.142 (Pi constant)	**K** = 1.78 Surface CO2 MSCF / Reservoir Barrel (WMU specific variable based on temperature and pressure)
r = 150 ft	**Sco2** = 0.50 (Estimated CO2 saturation within injection radius)
H ft = (Net pay thickness-well specific variable)	**LC** = Barrel Liquid / 5.614 SCF (volumetric conversion)

F = 0.266 (Ave. “C” sand porosity WMU)	**CV =** Cyclic CO2 Volume MSCF

TABLE II. PROPOSED CO2 INJECTION VOLUMES

WELL	“C” Sand Thickness	CO2 volume
	(Feet)	(MMCF)
17-2	21	63
17-4	38	113
17-14	~47 (22+)	140

Conclusion

Assuming that the WMU tests are mechanically and operational successful, what can we expect from this experiment?

If we assume that the average CO2 utilization obtained in our WMU field tests is 3 MSCF/STB, which was the cutoff used for differentiating the successful from the unsuccessful tests for the researchers, then we should recover on the order of 105 MSTB of incremental oil for the total CO2 volume injected. This would have a major impact on cash flow as well as for reserves growth in several categories for the Company.