QUARTERLY TECHNICAL PROGRESS REPORT
FOR THE PERIOD ENDING JUNE 30, 2000

TITLE: FIELD DEMONSTRATION OF CARBON DIOXIDE MISCIBLE FLOODING IN THE LANSING-KANSAS CITY FORMATION, CENTRAL KANSAS

DOE Contract No. DE-AC26-00BC15124

Contractor: University of Kansas Center for Research, Inc.
2385 Irving Hill Road
Lawrence, KS 66044

DOE Program: Class II Revisited - Field Demonstrations

Award Date: March 8, 2000

Total Project Budget: $5,388,683

DOE Cost Amount: $1,892,094

Program Period: March 8, 2000 – March 8, 2006 (BP1 03/00-03/01, BP2 03/01-03/05, BP3 03/05-03/06)

Reporting Period: April 1, 2000 – June 30, 2000

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DISCLAIMER:

ABSTRACT:

Currently work is being performed on Tasks 1.1, 1.2, 1.3, 1.4, 7.0 and 8.0. Well data and lease production history data are being collected, inventoried and scanned for web access. Core, log, and engineering analysis is being performed to better understand the reservoir system. Remediation of Colliver #18 was performed to allow injection testing and obtain pilot area permeability-height data. Collection of reservoir pressure data has been scheduled. The project has not reached any scheduled milestones to date. Progress is reported for the period from April 1, 2000 to June 30, 2000. Work in this quarter concentrated on compilation of Colliver and Carter lease data to reconstruct a recurrent data set and construction of a quantitative reservoir model for numerical reservoir simulation. At the demonstration site the Lansing-Kansas City oomoldic limestones are interpreted to represent three transgressive-regressive cycles which have been overprinted by a subaerial exposure event. Porosity and permeability decrease with depth from the top of the ‘C’ zone. Permeability-porosity relations for the L-KC at the demonstration site are consistent with oomoldic limestones across the central Kansas uplift though permeabilities are at the high-end for any given porosity. Capillary pressure measurements of core chips and plugs indicate that “irreducible” water saturation is well correlated with permeability. Work also involved unitization of the Colliver and Carter leases for optimum flooding and several technology transfer presentations. This quarterly report will concentrate on a brief summary of work performed under Tasks 1.1, 1.2, 1.3, 1.4, 7.0 and 8.0.

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INTRODUCTION

Objectives - The objective of this Class II Revisited project is to demonstrate the viability of carbon dioxide miscible flooding in the Lansing-Kansas City formation on the Central Kansas Uplift and to obtain data concerning reservoir properties, flood performance, and operating costs and methods to aid operators in future floods. The project addresses the producibility problem that these Class II shallow-shelf carbonate reservoirs have been depleted by effective waterflooding leaving significant trapped oil reserves. The objective is to be addressed by performing a CO_2 miscible flood in a 40-acre pilot in a representative oomoldic limestone reservoir in the Hall-Gurney Field, Russell County, Kansas. At the demonstration site, the Kansas team will characterize the reservoir geologic and engineering properties, model the flood using reservoir simulation, design and construct facilities and remediate existing wells, implement the planned flood, and monitor the flood process. The results of this project will be disseminated through various technology transfer activities.

Project Task Overview -

Activities in Budget Period 1 (03/00-03/01) involve reservoir characterization, modeling, and assessment:

- Task 1.1- Acquisition and consolidation of data into a web-based accessible database
- Task 1.2 - Geologic, petrophysical, and engineering reservoir characterization at the proposed demonstration site to understand the reservoir system
- Task 1.3 - Develop descriptive and numerical models of the reservoir
- Task 1.4 - Multiphase numerical flow simulation of oil recovery and prediction of the optimum location for a new injector well based on the numerical reservoir model
- Task 2.1 - Drilling, sponge coring, logging and testing a new CO2 injection well to obtain better reservoir data
- Task 2.2 - Measurement of residual oil and advanced rock properties for improved reservoir characterization and to address decisions concerning the resource base
- Task 3.1 - Advanced flow simulation based on the data provided by the improved characterization
- Task 3.2 - Assessment of the condition of existing wellbores, and evaluation of the economics of carbon dioxide flooding based on the improved reservoir characterization, advanced flow simulation, and engineering analyses
- Task 4.1 – Review of Budget Period 1 activities and assessment of flood implementation

Activities in Budget Period 2 (03/01-03/05) involve implementation and monitoring of the flood:

- Task 5.1 - Remediate all wells in the flood pattern
- Task 5.2 - Re-pressure the pilot area by water injection
- Task 5.3 - Construct surface facilities
- Task 5.4 - Implement CO_2 flood operations
- Task 5.5 - Analyze CO_2 flooding progress - carbon dioxide injection will be terminated at the end of Budget Period 2 and the project will be converted to continuous water injection.

Activities in Budget Period 3 (03/05-03/06) will involve post-CO2 flood monitoring:

- Task 6.1 – Collection and analysis of post-CO2 production and injection data

Activities that occur over all budget periods include:

- Task 7.0 – Management of geologic, engineering, and operations activities
- Task 8.0 – Technology transfer and fulfillment of reporting requirements

EXECUTIVE SUMMARY:

Currently work is being performed on Tasks 1.1, 1.2, 1.3, 1.4, 7.0 and 8.0. Well data and lease production history data are being collected, inventoried and scanned for web access. Core, log, and engineering analysis is being performed to better understand the reservoir system. Remediation of Colliver #18 was performed to allow injection testing and obtain pilot area permeability-height data. Collection of reservoir pressure data has been scheduled. The project has not reached any scheduled milestones to date. Progress is reported for the period from April 1, 2000 to June 30, 2000. Work in this quarter concentrated on compilation of Colliver and Carter lease data to reconstruct a recurrent data set and construction of a quantitative reservoir model for numerical reservoir simulation. At the demonstration site the Lansing-Kansas City oomoldic limestones are interpreted to represent three transgressive-regressive cycles which have been overprinted by a subaerial exposure event. Porosity and permeability decrease with depth from the top of the ‘C’ zone. Permeability-porosity relations for the L-KC at the demonstration site are consistent with oomoldic limestones across the central Kansas uplift though permeabilities are at the high-end for any given porosity. Capillary pressure measurements of core chips and plugs indicate that “irreducible” water saturation is well correlated with permeability. Work also involved unitization of the Colliver and Carter leases for optimum flooding and several technology transfer presentations. This quarterly report concentrates on a brief summary of work performed under Tasks 1.1, 1.2, 1.3, 1.4, 7.0 and 8.0.

RESULTS AND DISCUSSION:

Task 1.1 ACQUISITION OF DATA AND MATERIAL

Well file data obtained from Murfin Drilling files have been inventoried and images scanned for presentation on the web. Colliver and Carter lease production histories, pressures, and dates of when wells came online have been documented and are being compiled into a recurrent database suitable for numerical simulation.

The CO_2-related web site continues to grow:http://www.kgs.ukans.edu/ERC/index.html.

TASK 1.2 RESERVOIR CHARACTERIZATION

1.2.1 Geologic Characterization - The Lansing-Kansas City ‘C’ zone reservoir has been characterized geologically in the Colliver-Carter area using available cuttings and wireline logs. Based on correlation with outcrop Lansing-Kansas City and log signatures, the Lansing-Kansas City section comprises a succession of alternating marine limestones and shallow marine to nonmarine shales deposited during the Upper Pennsylvanian Series. Seas episodically covered Kansas and the Midcontinent leading to the accumulation of limestones and shales. The extreme fluctuations in sea level lead to the advance and retreat of multiple shorelines, locally characterized by high-energy conditions, much like portions of the present day Bahama Platform. The shoal water limestones of the Lansing-Kansas City were locally oolitic grainstones, a common lithology that serves as the main petroleum reservoir in these rocks in Kansas. The ooids are typically distributed as bars, spillover lobes, deltas, and beaches exhibiting potentially complex sets of lobes, pods, and lenses of oolite deposited during a particular cycle and sea level conditions. Geometries of beds within oolitic grainstones can include cross stratification, large foresets, and cut-and-fill structure.

Based on thin section analysis, original primary porosity was interparticle and could range up to 40 percent of the volume of the rock. This pore space was modified by early post-depositional processes including alteration by rainwater (meteoric) and shallow groundwater moving through the rock leading to both dissolution of ooids and cementation of original interparticle porosity. Most Pennsylvanian ooids were originally aragonite and tended to dissolve and recrystalize after coming into contact with percolating fresh rainwater or shallow groundwater. While Lansing-Kansas City oolitic grainstones were formed by the deposition of ooids, oomoldic grainstones in the Lansing-Kansas City of Hall-Gurney Field and the demonstration site are dominated by molds of ooids. These oomoldic pores are the dominant porosity found in oolitic grainstones of the Pennsylvanian in the Midcontinent. The geometries of the permeable (effective) reservoir rock vary considerably as a function of: 1) sedimentation of the oolites and 2) post depositional alteration including dissolution, cementation, and structural deformation.

At the demonstration site the reservoir facies has been confirmed to be oomoldic limestone on the basis of cuttings description. Figure 1 illustrates a typical Lansing ‘C’ zone oomoldic limestone in both direct image and under plane light in thin section with blue-dye epoxy filling pores. Scanned images of cuttings will be placed on the web site in the next quarter.

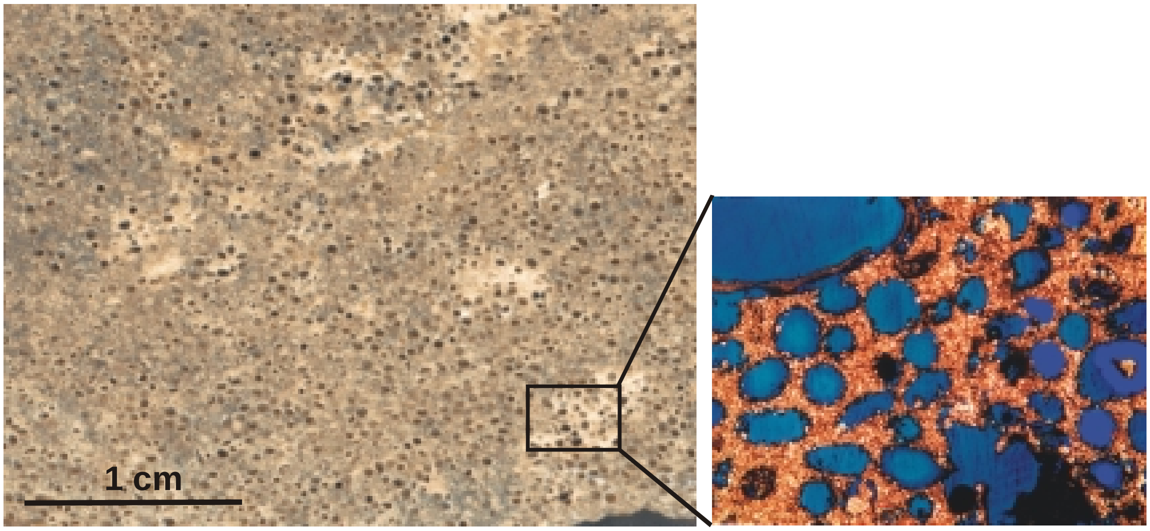
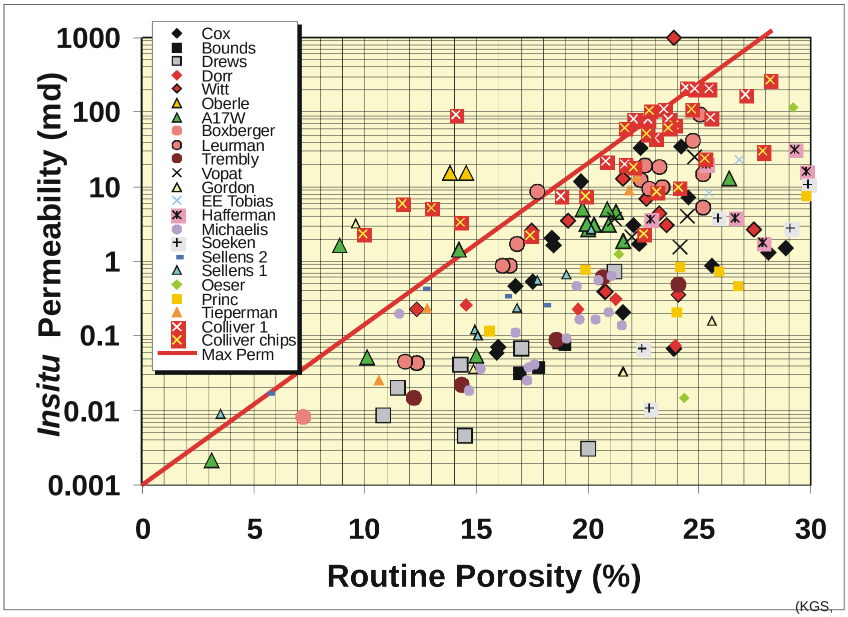


Figure 1. Lansing-Kansas City oomoldic limestone and plane light thin section showing blue-dye epoxy-filled pore space.

Examination of wireline log gamma ray and unscaled neutron porosity depth profiles indicates that the Lansing ‘C’ zone at the demonstration site consists of either three transgressive-regressive cycles or three stacked beds. For maximum numerical simulation accuracy the C zone has been divided into six layers, termed C1 through C6 as described below.

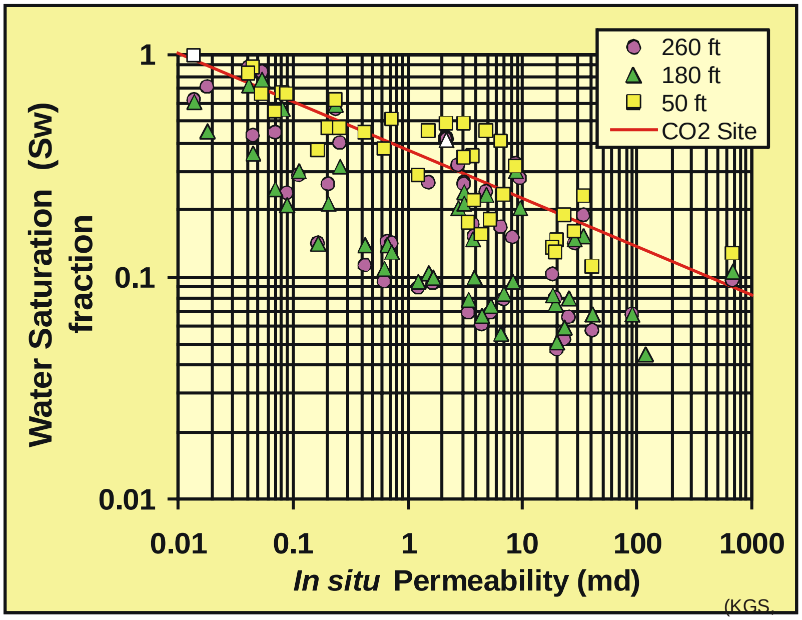
Core Petrophysics - Preliminary routine and special core analysis on oomoldic limestones from the Central Kansas Uplift has been completed and the data analyzed. Full diameter porosity and permeability data for the Colliver #1, measured by Phillips Oil Company in 1936, were found in the well files. These full-diameter permeabilities are some of the highest values reported or measured to date though they fall below the maximum permeability versus porosity trend for Central Kansas Uplift oomoldic limestones as shown below on Figure 2. Core chips were also obtained for the Colliver #12. Porosity and grain density were measured on trimmed chips, generally measuring approximately 2-6 cm^3, after these measurements the chips were embedded in epoxy with two end faces exposed for permeability testing. Full diameter and chip permeability versus porosity trends are shown on Figure 2. Differences between chip and whole core permeabilities may reflect such factors as microfracturing, vuggy porosity channels, differences in oomoldic limestone properties, or other parameters. These differences will be resolved using data obtained on the new injector well core under Task 2.



(KGS, 2000)

Figure 2. *In situ* Klinkenberg permeability versus routine porosity for Lansing-Kansas City oomoldic limestone cores obtained from wells in reservoirs lying along the Central Kansas Uplift. Estimated maximum permeability for unfractured and non-vuggy rocks is shown as red trendline. While scatter for total population is high, inidividual wells exhibit significantly less scatter.

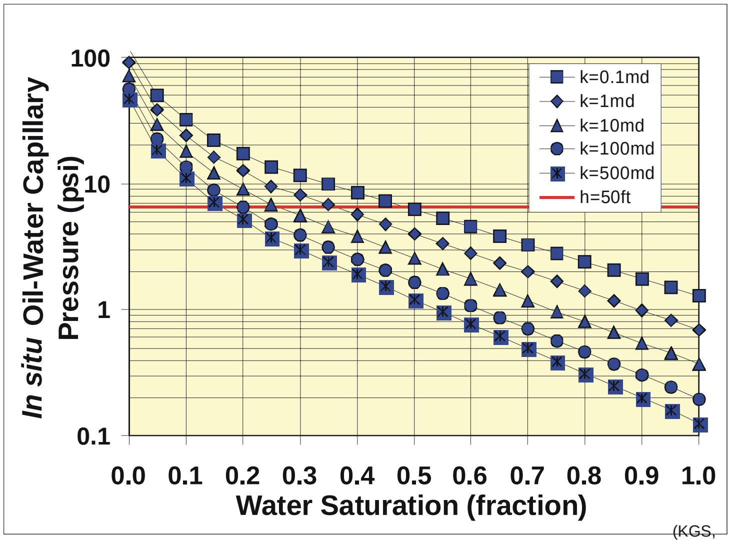
Air-brine capillary pressure measurements were performed on a range of Lansing-Kansas City oomoldic limestone samples to obtain a trend to predict initial water saturation in the reservoir. Capillary data indicate very low irreducible water saturations for oil column heights greater than 180 feet above free water level. Analysis of the Hall-Gurney structure near the Colliver and Carter leases indicates that the reservoir lies approximately 45-55 feet above free water level (Figure 3) which exhibit higher saturations.



(KGS, 2000)

Figure 3. Water saturation at various oil column heights above free water level versus permeability for Lansing-Kansas City oomoldic limestones.

Mercury capillary pressure was measured on eight samples including oomoldic limestones distributed across the Central Kansas Uplift and a core chip from the Colliver #12. Selected samples spanned nearly the complete range in porosity (16.8%-24.9%) and permeability (0.68md – 91.9md) exhibited by the reservoir quality Lansing-Kansas City oomoldic limestones from the Central Kansas Uplift available in the study set.



(KGS, 2000)

Figure 4. Generalized capillary pressure curves for oomoldic limestones constructed using formulas. Curvature below 15% Sw was induced by adjustment multiplier and is not predicted by the equations.

Examination of the capillary pressure curves for the eight samples reveals that many samples exhibit a near log-linear trend between wetting phase saturation (assumed to be water in the reservoir) and oil-brine height above free water level. This would also translate to a log-linear relationship between wetting-phase saturation and reservoir oil-brine capillary pressure.

Comparison between samples of different permeability indicates that capillary pressures decrease with increasing permeability at any given saturation. This is a typical trend for most rocks. Analyzing the relationship between the change in capillary pressure and permeability, an equation was constructed that provides approximate capillary pressure curves for any given permeability (Fig. 4). This equation takes the form:

$$Pc = 10^{(A\ Sw\ +\ B)}\ (\rho_{water}-\rho_{oil})$$

Where Pc is reservoir oil-brine capillary pressure (psia), Sw is water saturation (fraction), ρ_{water} and ρ_{oil} are water and oil density (g/cc), and A and B are constants that vary with permeability. These constants can be predicted from permeability using:

$A = -0.1663 \log_{10}\mathit{Permeability}$ (md) –1.5186
$B = 0.1088 \log_{10}\mathit{Permeability}$ (md) +2.2476

These equations provide generalized capillary pressure curves that approximate the general relationships shown by the samples studied.

Thin sections have been prepared for twenty cuttings and core chips from the Colliver lease. These are all oomoldic limestones but exhibit a range of pore types including isolated oomolds, connected oomolds, vuggy, microcrystalline, fractured, interparticle, and exhibit macroporous cement.

Because core is not yet available from the Colliver or Carter leases or from more permeable Lansing-Kansas City oomoldic limestone, imbibition water-oil relative permeability curves were obtained from data provided by McCoy Petroleum measured on oomoldic limestone from the Marmaton Formation , Amazon Ditch East Field, Six-M Farms “A” No. 3-22, Finney County, KS. These limestones exhibited properties very similar to the Lansing ‘C’ zone with porosity of 24-25% and permeability of 20-28 md. These data will serve as the basis for initial relative permeability curves for the numerical simulator until core are obtained from the new injection well.

Log Petrophysics - Wireline logs for 41 wells in the area of the pilot have been obtained, digitized and analyzed. The majority of these logs are older gamma ray – neutron logs with no resistivity logs but these appear to provide adequate porosity evaluation within $\underline{+}2$ porosity percent. To convert neutron response to porosity the logs were calibrated using the standard log-linear relationship:

$$\text{Porosity (\%)} = 10^{(A*Neutron\ +\ B)}$$

Where A is the slope of the correlation between $\log_{10}$Porosity and neutron response and B is the intercept. These constants were derived using a log-linear straight-line relationship between the two points: 40% porosity-minimum Neutron response, 1% porosity-maximum neutron response. Using this correlation neutron log response was converted into porosity.

1.2.2 Fluid Characterization – Oil from the Letsch #7, one mile east of the Colliver lease was analyzed for minimum miscibility pressure prior to start of the DOE contract. Further analysis of MMP will wait until a lease sample is available. Interfacial tension was measured on a Letsch #10 oil sample and found to be 28.6 dyne/cm at 25°C. Oil chemical composition was measured by Core Laboratories on the Letsch #7 oil sample.

1.2.3 Engineering Characterization – Colliver and Carter production history data are being compiled. These will provide the basis for material balance calculations in the next quarter.

TASK 1.3 RESERVOIR MODEL

A qualitative and quantitative preliminary reservoir model has been constructed for the Colliver and Carter leases. The Lansing ‘C’ interval has been characterized as being composed of three stacked units between which the vertical communication is uncertain (Figure 5)

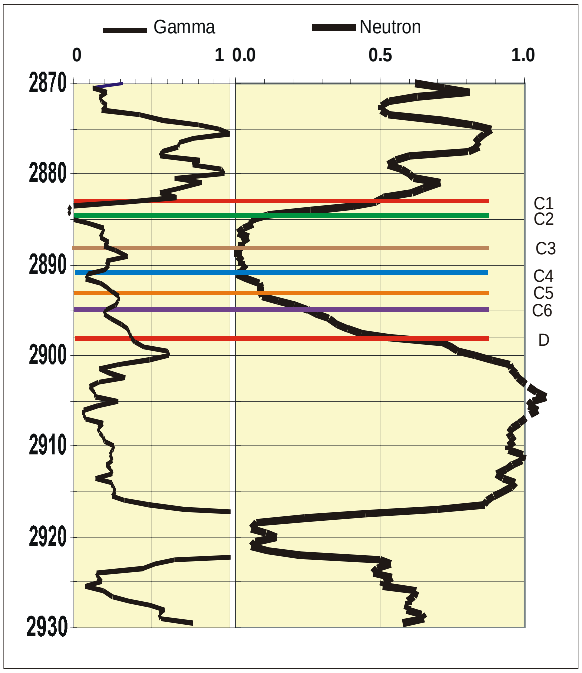


Figure 5. Colliver #18 normalized gamma ray-unscaled neutron log showing six C zone layers and three cycles. The Colliver #18 exhibits some of the best porosity compared to all wells in both leases.

Because permeability changes by a factor of 2 for every 1 porosity unit change, each of the three layers has been divided into an upper and lower layer to minimize permeability variance within a layer and error associated with layer averaging. Overall, the C zone deceases in porosity and permeability from top to bottom. The six layers have been termed C1 through C6. This division allows more accurate delineation of saturations and flooding behavior in each layer.

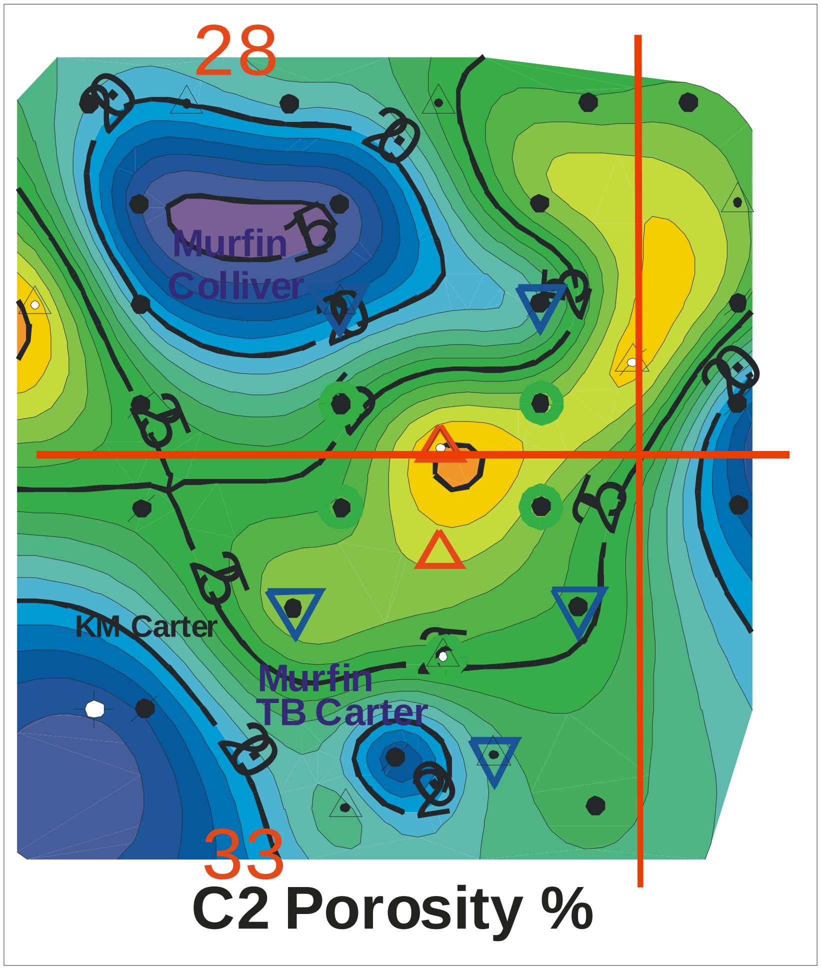
Average Layer Properties

C1: 8 md, 18.8%
C2: 150 md, 25.8%
C3: 40 md, 22.0%
C4: 6 md, 19.4%
C5: 2 md, 14.7%
C6: 0.3 md, 12.0%

Porosity and calculated permeability were mapped for each layer for the Colliver and Carter leases. An example of the porosity distribution is shown in Figure 6.

Figure 6. Example of porosity distribution in layer C2 for Colliver and Carter leases.

14S-13W Russell Co., Kansas



Task 1.4 Reservoir Simulation (Phase I)

Measured oil composition was input into the VIP numerical simulator. Numerical simulations successfully matched the measured PVT properties and the flood behavior of previously conducted slimtube experiments.

Simulations of the entire flood area were performed to determine surrounding water injection requirements for pressuring up the flood area to minimum miscible pressure (MMP) and maintaining pressures during flooding. Pressure-up phase was simulated using a single layer model, injection into the five containment wells and the two CO2 injectors at 350 BWPD, initial BHP of 500#. It required 165 days to pressure up the entire flood area to 1800 psi in the center of the pattern, 1500 psi in the pattern, and 1200 psi one-half mile from the pattern. Confinement and pressure maintenance will be further evaluated with wells outside the pattern allowed to produce. These results indicate that pressure control should not be a problem.

Using the compiled lease production histories a recurrent database is being constructed with format suitable for input to VIP. History matching and CO2 flood simulations will be performed in the next quarter to determine the optimum position of the new CO2 injection well.

TASK 7.0 PROJECT MANAGEMENT

To facilitate optimum flood design and use of a common tank battery Murfin petitioned the KCC for unitization of the Colliver and Carter leases. Seventy seven percent of royalty owner signatures were acquired before the hearing. There was 30 minutes of testimony and no opposition. Unitization was granted with a 400-acre unit created.

Two organizational meeting were held 04/27 and 06/08 with the following personnel present: MV Energy) Jim Daniels, Larry Jack; TORP) Paul Willhite, Rich Pancake, Don Green; KGS) Alan Byrnes, Marty Dubois, Lynn Watney, Tim Carr; Kinder-Morgan) Lanny Schoeling (via phone); PTTC) Rodney Reynolds.

Lanny Schoeling of Kinder Morgan reported that there is no change in status for the CO2 project with the purchase of Shell CO2 Company by Kinder Morgan. He also indicated that Kinder-Morgan would not need to sign a new letter of commitment since they had an equity position in Shell CO2 Company. He anticipates that Kinder-Morgan will be more aggressive in seeking new markets.

TASK 8.0 TECHNOLOGY TRANSFER

Four principal technology transfer activities were performed in this quarter. Some of these involved presentation of work conducted prior to the initiation of the DOE project combined with data obtained during the DOE project.

1) A poster presentation was presented at the Annual convention of the AAPG, April 16-19, New Orleans, LA:

Oomoldic reservoirs of central Kansas: controls on porosity, permeability, capillary pressure and architecture

Byrnes, Alan P.; Watney, W. Lynn; Guy, Willard J.; Gerlach, Paul; Kansas Geological Survey

Cyclic carbonate strata of the Pennsylvanian Lansing-Kansas City groups represent important enhanced oil recovery targets on the Central Kansas Uplift and thus require understanding of controls on reservoir properties and architecture. Interaction of changing sea level and local episodic processes, such as tidal currents along a broad topographically high shelf area, led to accumulation and local reworking and redeposition of elongate stacked, shingled, and cross-cutting oolite sand bars (0.5-10 m thick). Subaerial exposure and meteoric water percolation led to microporous cementation around the aragonite ooids and often dissolution of the ooids and variable development of vuggy porosity. Resulting oomoldic grainstones, the principal reservoir lithofacies, underwent variable degrees of early or later fracturing and crushing, providing connection between otherwise isolated oomolds. Grain size variation, location on oolite buildups and local topography, and interbedded carbonate mud (aquitards) influenced the nature and extent of diagenetic overprinting and resulting permeability-porosity, and capillary pressure properties.

The relation between permeability (0.01-400 md) and porosity (5-35%) is significantly influenced by the connectivity of the oomoldic pores complicating the use of porosity as an effective predictor of permeability without information about lithology. For “average” connectivity: log*Permeability*(md)=0.16**Porosity*(%)-2.32. Vug and fracture enhanced connectivity and oomold isolation can respectively increase and decrease permeability by a factor of up to 25X. Irreducible water saturation (*Siw*) and residual oil saturation after waterflooding (*Sor,w*) are also strongly controlled by connectivity and correlate highly with permeability: *Siw*(%) = 35.7*exp(-0.46*log*Permeability*(md)), *Sor,w*(%) = -20.9* log*Permeability*(md) + 59. These oomoldic reservoirs provide insight into the interactions of rock fabric-architecture-diagenesis on reservoir properties.

2) A talk was presented to the Kansas Geological Society by Martin Dubois of the Kansas Geological Survey on May 18 reviewing the economics of CO2 flooding in central Kansas type reservoirs. The content of this talk is presented on the CO2 website.

3) A paper was published in the Oil & Gas Journal, June 5, pages 37-41, entitled “ Economics show CO2 EOR potential in central Kansas” by Martin K. Dubois, Alan P. Byrnes, Richard E. Pancake, G. Paul Willhite, and Lanny G. Schoeling. A reprint is attached.

4) A talk was presented by Alan P. Byrnes at the NPTO 2000 Petroleum Technology Contract Review Meeting, June 26 in Denver, CO. The content of this talk is presented on the CO2 website.

CONCLUSIONS:

Petrophysical analysis of core chips and previous analysis of whole core indicate that the L-KC at the demonstration site is generally similar to other L-KC oomoldic limestone reservoirs on the central Kansas Uplift. Development of correlations between petrophysical properties provides the basis for quantification of reservoir properties from unscaled neutron logs. A geomodel of the Carter-Colliver leases will provide the basis for prediction of reservoir performance and will be used to designate the location of the new CO2 injection well to be drilled in the third quarter.

REFERENCES:

Byrnes, A.P., Watney, W.L., Guy, W.J., Gerlach, P., 2000, “Oomoldic reservoirs of central Kansas: controls on porosity, permeability, capillary pressure, and architecture”: Proceedings AAPG/SEPM Annual Convention, April 16-19, 2000, New Orleans, LA, p. A22