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University of North Dakota
15 North 23rd Street, Stop 9018 • Grand Forks, ND 58202-9018 • P. 701.777.5000 • F. 701.777.5181
www.undeerc.org

July 28, 2016

Ms. Karlene Fine
Executive Director
North Dakota Industrial Commission
600 East Boulevard Avenue
State Capitol, 14th Floor
Bismarck, ND 58505-0310

Dear Ms. Fine:

Subject: Project Status Report Entitled "Improved Characterization and Modeling of Tight Oil Formations for CO_2 Enhanced Oil Recovery Potential and Storage Capacity Estimation," Contract No. G-036-072; EERC Fund 20561

Attached is a hard copy of the subject project status report for the period of April 1 through June 30, 2016.

If you have any questions, please contact me by phone at (701) 777-5287, by fax at (701) 777-5181, or by e-mail at jsorensen@undeerc.org.

Sincerely,

James A. Sorensen
Principal Geologist

JAS/rlo

Attachment

IMPROVED CHARACTERIZATION AND MODELING OF TIGHT OIL FORMATIONS FOR CO_2 ENHANCED OIL RECOVERY POTENTIAL AND STORAGE CAPACITY ESTIMATION

Quarterly Progress Report
April 1 – June 30, 2016

EXECUTIVE SUMMARY

The injection of carbon dioxide (CO_2) into oil reservoirs for simultaneous enhanced oil recovery (EOR) and CO_2 storage continues to be an important tool with the potential to reduce anthropogenic CO_2 emissions to the atmosphere. CO_2 EOR and storage operations in conventional oil reservoirs have been conducted at many locations for decades, and the mechanisms that control successful EOR and storage in conventional reservoirs are well understood. However, there has been little experience injecting CO_2 into unconventional tight oil formations, and the controlling factors are not well understood. The Energy & Environmental Research Center (EERC) is conducting a research program to evaluate the characteristics of the rocks and physical–chemical mechanisms affecting CO_2 permeation and oil extraction in tight, organic-rich, oil-wet and mixed-wet systems. The project is using samples from the Bakken Formation in North Dakota, which is one of the most prolific oil-producing unconventional tight formations in the world. The objective is to assess and validate CO_2 transport and flow in the Bakken by conducting a series of laboratory- and modeling-based activities to determine the effects of micro- and nanoscale fracture and pore networks, as well as the nature of the wetting fluid, on CO_2 storage and EOR in the Bakken tight oil formation. This effort will also generate data to further illuminate the roles that the shale members may play with respect to CO_2 storage, containment, EOR or, possibly, even all three. The overall project goal will be accomplished through two phases. The Phase I objective is the development of advanced characterization methods to better understand and quantify the petrophysical and geomechanical factors that control CO_2 and oil mobility within tight oil formation samples. Phase II has two objectives. The first objective of Phase II is the determination of CO_2 permeation and oil extraction rates in tight reservoir rocks and organic-rich shales. The second Phase II objective is to integrate the laboratory-based CO_2 permeation and oil extraction data and the characterization data from Phase I into geologic models and dynamic simulations to develop predictions of CO_2 storage capacity and EOR in the Bakken tight oil formation.

During this quarter, laboratory activities were conducted and completed under Subtask 2.3 to characterize the kerogen and bitumen content and their ability to absorb CO_2 of selected Bakken samples. This resulted in the achievement of Milestone 12. Phase II activities were initiated, including laboratory-based experiments under Task 4 – CO_2 Transport, Permeation, and Oil Extraction Testing, and modeling activities under Task 5 – MMPA, Modeling, and Simulation. A paper entitled "The Use of Advanced Analytical Techniques to Characterize Micro- and Nanoscale Pores and Fractures in the Bakken" was prepared and submitted to the 2016 Unconventional Resources Technology Conference (URTeC). The paper will be published as part of the conference proceedings and will serve as Deliverable 5. The results of thin-section analyses, mineral maps derived from standard scanning electron microscopy (SEM), micro- and nanoscale fracture analysis, and the results of micro- and nanoscale fractures and pores using

micro-computed tomography (micro-CT) and advanced SEM techniques at Ingrain were compiled into a Phase I Interim Report which was provided to the Technical Monitor.

Task 1.0 – Project Management and Planning

Monthly project progress summaries were compiled and provided to the U.S. Department of Energy (DOE) Technical Monitor. During this quarter, the Phase I Interim Report was prepared and submitted to the Technical Monitor.

Task 2.0 – Sample Selection and Detailed Baseline Characterization

Subtask 2.3 is focused on conducting a laboratory-based evaluation of the effects of CO_2 on kerogen and bitumen in Bakken shale. The goal of the subtask is to generate data that provides insight regarding the effects that kerogen and bitumen may have on CO_2 storage and EOR in shales. In particular, kerogen and bitumen may act as a chemical sorbent phase that could significantly increase the CO_2 storage capacity of shales over the capacity that would be expected based only on a volume/pressure basis. In this quarter, RockEval testing to develop data regarding the maturity of the shale samples (maturity can be correlated to kerogen/bitumen content) was conducted. A set of RockEval experiments using CO_2 were completed. Insight regarding the effect that CO_2 has on kerogen and bitumen were developed by comparing the results of the experiments that used inert gas in the standard RockEval maturation process with those that used CO_2. Experiments were also conducted using a magnetic suspension balance to compare and quantify the ability of Bakken shale and Middle Bakken samples to sorb CO_2. We have speculated that the kerogen content in the Upper and Lower Bakken shales may lead to increased CO_2 storage capacity based on chemisorption of the CO_2 into (or onto) the shale kerogen. The results of those experiments showed that Bakken shale samples averaged approximately 7 mg CO_2 weight gain per gram of shale. In contrast, Middle Bakken samples showed essentially no weight gain. Initial evaluation and interpretation of the data indicates that there is a strong correlation between the kerogen content of organic-rich shales and their ability to sorb CO_2.

Task 3.0 – Development of Improved Methodologies to Identify Multiscale Fracture Networks and Pore Characteristics

The results of micro-CT and advanced SEM techniques on the MOC (Marathon Oil Company) samples, as well as the data on bulk density, organic matter volume, mineralogy, porosity, fracture and pore throat geometry, and distribution at the micro- and nanoscales were compiled into an interim report which was provided to the Technical Monitor.

ACCOMPLISHMENTS

Major Goals of the Project

The goal of this project is to develop advanced analytical characterization and geomodeling techniques to better estimate the potential for CO_2-based EOR and CO_2 storage in unconventional tight oil formations. The project will accomplish this goal by using samples

collected from the tight, fractured reservoir and oil-wet, organic-rich shales within the Bakken petroleum system to do the following:

- Develop methods to better detect and characterize the macro-, micro-, and nanoscale pores and fracture networks within tight, fractured reservoirs and within organic-rich shales.

- Determine if there are significant correlations between fracture network characteristics and the physical, geochemical, and/or geomechanical properties of the rock that can be used to improve well log calibration and interpretation, thereby allowing for improved identification of fracture networks using well logs.

- Determine the rates of CO_2 permeation within, and oil extraction from, the matrix of tight oil formation rocks, including oil-wet, organic-rich shales.

- Assess how CO_2 capillary entry pressure at the reservoir–seal interface is affected by the wetting fluid of tight oil formation rocks, including oil-wet and mixed-wet reservoir rocks and oil-wet, organic-rich shales.

- Develop improved methods to integrate detailed rock characterization data into geocellular and simulation models to improve their accuracy in predicting the CO_2 storage capacities and potential incremental oil production through EOR in a tight oil reservoir and to evaluate the ability of oil-wet, organic-rich shales to store and/or contain CO_2 and possibly produce oil.

Task 1.0 – Project Management and Planning

Monthly project progress summaries and Deliverable 6 (D6) – Phase I Interim Report were submitted to the DOE Technical Monitor. A representative of the EERC presented a summary of the Phase I results at the Carbon Capture, Utilization & Storage Conference in Tysons, Virginia, on June 15. James Sorensen attended the Society of Petroleum Engineers (SPE) Forum on Key Factors for Success in Unconventional Reservoir Development in San Antonio, Texas, from June 13 to 17 and served as Co-Chair for two sessions of that Forum, including a session on reservoir characterization and a session on EOR. Conversations were held with representatives of MOC and the North Dakota Department of Mineral Resources about the progress of the project and future activities.

Task 2.0 – Sample Selection and Detailed Baseline Characterization

Subtasks 2.1 and 2.2 were completed in a previous quarter.

Subtask 2.1 – Sample Identification and Selection

This subtask is complete.

Subtask 2.2 – Laboratory Determination of Baseline Rock Properties

This subtask is complete.

Subtask 2.3 – Laboratory Evaluation of the Effects of CO_2 on Kerogen and Bitumen in Bakken Shale

A series of laboratory experiments under reservoir temperature and pressure conditions on samples of Bakken shale were conducted to develop an improved understanding of the kerogen and bitumen content of Bakken shale samples. In this quarter, the final round of RockEval testing was conducted to develop data regarding the maturity of the shale samples (maturity can be correlated to kerogen/bitumen content). A total of 23 samples of Upper Bakken shale were crushed and sieved to 0.5–2-mm particle size and used to investigate the thermal maturation of kerogen organics at temperatures ranging from 300° to 370°C and times ranging from 5 to 1004 hours. Exposures of the shale were conducted in water both with and without the presence of 5000-psi CO_2. Experiments were also conducted using a magnetic suspension balance to quantify the mass uptake of CO_2 in rock samples from the Upper and Lower Bakken shales and selected Middle Bakken lithofacies. The results are then compared to determine the ability of Bakken shale and Middle Bakken samples to sorb CO_2. We have speculated that the kerogen content in the Upper and Lower shales may lead to increased CO_2 storage capacity based on chemisorption of the CO_2 into (or onto) the shale kerogen. A Rubotherm magnetic suspension balance was used with approximately 10-gram samples to measure the weight gain under 5000-psi and 110°C exposure to CO_2. Upper and Lower shale samples averaged approximately 7 mg CO_2 weight gain per gram of shale. In contrast, Middle Bakken samples showed essentially no weight gain. The combined results of the RockEval testing and the microbalance testing indicate that samples higher in kerogen have a greater capacity to sorb CO_2. The results suggest that there is a strong correlation between shale maturity and CO_2 sorption capacity. The studies being conducted under this subtask are considered to be complete, thereby resulting in the achievement of Milestone 12 (M12 – Completion of Kerogen and Bitumen Studies). Results will be summarized in a paper (D10 – Manuscript – Effects of Kerogen-Bitumen Content on CO_2 Storage and EOR in Tight Oil Formations) to be presented at a future relevant technical conference yet to be determined.

Task 3.0 – Development of Improved Methodologies to Identify Multiscale Fracture Networks and Pore Characteristics

Subtask 3.1 – Core-Scale Fracture Analysis

This subtask is complete.

Subtask 3.2 – Macrofracture Characterization

This subtask is complete.

Subtask 3.3 – Micro- and Nanoscale Fracture and Pore Analysis

This subtask is complete.

Subtask 3.4 – Development of Multiscale Pore and Fracture Models

The laboratory-based rock characterization information was used to develop a multiscale pore and fracture model for use in the development of a geologic model. Specifically, fractal analysis of fracture networks and pore distributions were conducted on a range of scales, from the nano- and microscale (using field emission SEM) to the macroscale (using conventional SEM, optical microscopy, ultraviolet fluorescence, and visual core analysis). Techniques described in the literature to characterize the fractal properties of features and to develop multiscale models of fracture and pore networks were used for this effort. This quarter included the finalization of fractal modeling in an attempt to estimate sample permeability through image analysis techniques. The results of these analyses were compared to mercury injection capillary pressure analyses collected through Task 2. The results of the comparative analysis were inconclusive. Significant, correlative variation in fractal dimension with respect to either lithofacies or scale were not observed, which means the application of the fractal dimension data, using the techniques described in the literature, could not be correlated to key rock characteristics such as permeability or pore throat size distribution. Because of the lack of statistically valid correlations between the fractal analysis results and the measured properties of the rocks used in this study, the decision was made to not use the fractal dimension data as part of the efforts to scale the micro- and nanoscale characterization data up to larger scales. This decision was supported by conversations with industry and academic modeling experts who attended the SPE Forum described in Task 1, who expressed experiencing similar challenges when they attempted to incorporate fractal analysis techniques as part of their tight oil formation modeling efforts. It may be possible to develop new approaches to fractal analysis that could yield more correlative results and therefore be more useful in terms of modeling, but the pursuit of new approaches to fractal analysis is beyond the scope of this project.

Despite the challenges with the fractal analysis efforts, the laboratory-derived characterization data on the core used in Subtasks 2.2, 2.3, 3.1, 3.2, and 3.3 were still incorporated into models using other data integration techniques. In particular, the CT and micro-CT data were processed in novel ways using data-processing techniques normally applied to seismic data sets, which facilitated the integration of that data into geomodels constructed under Subtask 3.4. The use of those processing techniques enabled the project team to identify strong correlations between microfracture occurrence and lithofacies type. Those correlations are discussed in a paper entitled “The Use of Advanced Analytical Techniques to Characterize Micro- and Nanoschale Pores and Fractures in the Bakken,” which was prepared and submitted for presentation to the 2016 Unconventional Resources Technology Conference (URTeC). One of the valuable lessons learned from the Subtask 3.4 activities was that the novel processing of CT and micro-CT data, when combined with the traditional rock characterization data yielded an improved understanding of the relationship between the rock matrix and pore systems within the Bakken Formation. This will ultimately lead to a better modeling of fracture flow, geochemical reactions, kinetic rates of reactions, and geomechanical properties affected by fluid flow that will be investigated in Task 4 and ultimately modeled in Task 5.

Task 4.0 – CO_2 Transport, Permeation, and Oil Extraction Testing

Subtask 4.1 – Determination of Permeation Rates in Tight, Fractured Reservoir Rocks

Under this subtask, flow-through permeability studies using a core sample sealed in a containment cell (e.g., Hassler cell) will be performed. During this quarter, the specific plans for the experimental design elements were finalized, and activities to set up the laboratory apparatus for the testing were initiated. Specific rock samples that will be used in the tests were identified. It is anticipated that initial flow-through testing on Middle Bakken samples will be started early in the next quarter.

Subtask 4.2 – Determination of CO_2 Permeation Rates in Organic-Rich Shale Rocks

Under this subtask, testing of the samples taken from the Upper and Lower Bakken shales (i.e. very low permeability samples) will be carried out using an approach in which a cylindrical rock sample will be exposed to CO_2 in a high-pressure vessel, and the appearance of CO_2 into a hole drilled through the center of the rock core will be monitored. During this quarter the specific plans for the experimental design elements were finalized. Based on recent experiences conducting similar tests on similar rocks as part of different project, it is anticipated that the experimental approach described in the SOPO may have some challenges. With that in mind, contingency plans were developed for different experiments that would also yield CO_2 permeation rates in Bakken shales should those challenges prove to be technically unfeasible or overly resource intensive. The experiments identified as contingency experiments would not require additional financial resources or time, as it is believed that the determination of whether or not the primary experimental plan can be successful will be made in its earliest stages, and the contingency experiments are very similar to other experiments conducted by the EERC for other project. Activities to set up the laboratory apparatus for the permeation rate testing were initiated. Specific rock samples that will be used in the tests were identified. It is anticipated that initial permeation rate testing on Bakken shale samples will be started early in the next quarter.

Subtask 4.3 – CO_2-Soluble Tracers

Under this subtask, CO_2 permeation rates and flow patterns (e.g., via microfractures and interconnected pores) in Bakken reservoir and shale samples will be determined using CO_2-soluble tracers. During this quarter, discussions were held with a vendor who deals extensively in the use of tracers in tight oil formations, including the Bakken. The results of the initial experimental activities in Subtask 4.1 and 4.2 will aid in the selection of specific tracers that will be used in the 4.3 tests, so it is anticipated that the Subtask 4.3 activities will likely be initiated in the late third quarter or early fourth quarter of 2016.

Subtask 4.4 – Hydrocarbon Extraction

Under this subtask, hydrocarbon extraction experiments will be performed on samples of Middle Bakken reservoir rocks and Upper and Lower Bakken shale rocks, and the rate profiles will be evaluated. Different geometries of reservoir and shale rock will be utilized to investigate

CO_2 extraction of hydrocarbons, and the extraction profiles will be fit to an exponential model. During this quarter, the specific plans for the experimental design elements were finalized, and activities to set up the laboratory apparatus for the testing were initiated and completed. Specific rock samples that will be used in the tests were identified, and hydrocarbon extraction testing on Middle Bakken reservoir rock and Upper and Lower Bakken shale samples was conducted. It is anticipated that hydrocarbon extraction testing will continue to be conducted over the course of the next quarter.

Task 5.0 – Multimineral Petrophysical Analysis (MMPA), Modeling, and Simulation

Subtask 5.1 – MMPA Analysis

Under this subtask, a detailed petrophysical analysis will be performed in order to correlate geophysical logs with laboratory data using industry standard software such as Schlumberger's Techlog petrophysical software. A multimineral petrophysical approach (MMPA) will be followed in order to match mineral volumes with zones with varying degrees of natural fractures. The MMPA analysis will be carried out to integrate the core analysis data from Phase I for core-to-log calibration. The rock characterization data generated in Phase I will be integrated and correlated with petrophysical well log data provided by MOC and the North Dakota Geological Survey. During this quarter, the Subtask 5.1 efforts were initiated by organizing the Phase I data and the well log data in such a way as to facilitate the execution of the MMPA analysis.

Subtask 5.2 – Geocellular Modeling

Under this subtask, integration of the characterization data and well log correlation and analysis in Tasks 2–4 will be carried out to develop a geocellular model. During this quarter, the construction of generic matrix models was initiated. The Subtask 5.2 efforts will rely to some extent on the Subtask 5.1 results, and the two subtasks will be conducted in close association with each other on an iterative basis.

Subtask 5.3 – Dynamic Simulation of Tight Oil Formation Reservoirs and Shales

Under this subtask, using the fractured reservoir and shale models created in Subtask 5.2, injection simulations will be performed to evaluate CO_2 storage efficiency, CO_2 and oil sweep efficiency and, ultimately, CO_2 storage capacities and potential for incremental oil production through various EOR schemes. A variety of parameters will be modified to investigate the effect of each on the resulting CO_2 storage efficiency, CO_2 and oil sweep efficiency, CO_2 storage capacity, and incremental oil production. These activities are scheduled to be initiated next quarter.

Subtask 5.4 – Best Practices Manual for CO_2 Storage and EOR Potential Estimation of Tight Oil Formations

Under this subtask, a best practice manual (BPM) on the development of estimates for CO_2 storage resources and EOR potential in tight oil formations, using the Bakken as a case study, will be prepared. This subtask is scheduled to be initiated in April 2017.

MILESTONE STATUS REPORT

Task/ Subtask	Milestone Title	Planned Completion Date	Actual Completion Date	Verification Method	Comments
1.1	M1 – Update Project Management Plan (PMP)	12/31/14	12/31/14	PMP file	
1.2	M2 – Kickoff Meeting	1/31/15	12/4/14	Presentation file	
2.1	M3 – First Samples Collected for Characterization	12/31/14	12/31/14	Status reported in subsequent quarterly report	
2.2	M4 – Completion of Baseline Sample Characterization	10/31/15	10/31/15	Sample characterization data sheets	
3.2	M5 – First Macroscale Fracture Data Sets Generated	6/30/15	6/30/15	Status reported in subsequent quarterly report	
3.3	M6 – Completion of Fracture Network Characterization	4/30/16	4/29/16	Interim report at conclusion of Phase I	
4.2	M7 – Completion of CO_2 Permeation Testing	2/28/17		Status reported in subsequent quarterly report	
4.4	M8 – Completion of Hydrocarbon Extraction Testing	7/31/17		Status reported in subsequent quarterly report	
5.1	M9 – MMPA (multimineral petrophysical analysis) Complete	10/31/16		Status reported in subsequent quarterly report	
5.2	M10 – Completion of Geocellular Models	12/31/16		Status reported in subsequent quarterly report	
5.3	M11 – Completion of Simulations	4/30/17		Status reported in subsequent quarterly report	
2.3	M12 – Completion of Kerogen and Bitumen Studies	4/30/16	4/29/16	Status reported in subsequent quarterly report	

FUTURE ACTIVITIES

Activities planned for the next quarter include the following:

- Under Subtask 4.1, initial flow-through testing on Middle Bakken samples will be started.
- Under Subtask 4.2, initial permeation rate testing on Bakken shale samples will be started.
- Under Subtask 4.4, hydrocarbon extraction testing will continue to be conducted.

PRODUCTS

Activities conducted during this reporting period resulted in three products, listed as follows:

- Phase I Interim Report.
- A paper entitled "The Use of Advanced Analytical Techniques to Characterize Micro- and Nanoschale Pores and Fractures in the Bakken" was prepared and submitted to the 2016 Unconventional Resources Technology Conference (URTeC) to be held in San Antonio, Texas, August 1–4.
- A presentation entitled "Improved Characterization and Modeling of Tight Oil Formations for CO_2 Enhanced Oil Recovery Potential and Storage Capacity Estimation" was presented at the Carbon Capture, Utilization & Storage Conference in Tysons, Virginia, on June 15.

CHANGES/PROBLEMS

No problems were experienced during the reporting period, and no changes or deviations from the formal statement of work were necessary.

APPROACH CHANGES

The research approach has not changed during this reporting period.

PERFORMANCE VARIANCES

There were no performance variances during this reporting period.

TECHNOLOGY TRANSFER

- A paper entitled "The Use of Advanced Analytical Techniques to Characterize Micro- and Nanoschale Pores and Fractures in the Bakken" was prepared and submitted to the 2016 Unconventional Resources Technology Conference (URTeC). The paper will be published as part of the conference proceedings and serve as Deliverable 5 (D5).
- A presentation entitled "Improved Characterization and Modeling of Tight Oil Formations for CO_2 Enhanced Oil Recovery Potential and Storage Capacity Estimation" was presented at the Carbon Capture, Utilization & Storage Conference in Tysons, Virginia, on June 15.